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WOODS HOLE OCEANOGRAPHIC INSTITUTION

Woods Hole, Massachusetts

Technical Report No. 11

on the

HYDROGRAPHY OF THE WESTERN ATLANTIC;

The Long Island and Block Island

Sounds

April 48

Prepared by Gordon A. Riley

Submitted to the Oceanographic Division

Hydrographic Office

Under Contract No. N6onr-277

Task 1, NR-083-004

With Office of Naval Research

April 1948

ABSTRACT

A description is presented of the temperature and salinity distribution in the Long Island and Block Island Sounds observed during nine cruises between 22 January 1946 and 5 January 1947. Maximum salinity values were obtained in the outer part of Block Island Sound, with a gradual decrease toward minimum values in the western part of Long Island Sound and various shallow, semi-enclosed areas. Horizontal temperature gradients were equally pronounced. The largest seasonal temperature variations were found in the shallow coastal zone, so that this region was colder in winter and warmer in summer than the deeper water offshore. Vertical temperature and salinity gradients were nearly always found, but the stability was small compared with offshore waters, presumably because of strong tidal mixing.

A quantitative analysis is made of the temperature and salinity distribution in Long Island Sound. It is shown that the main features of this distribution can be accounted for by the interaction of a few oceanographic and meteorological phenomena - namely, tidal currents, water transport, horizontal and vertical turbulence, freshwater drainage and surface heat exchanges.

INTRODUCTION

The following report describes the results of nine cruises of the research vessels PHYSALIA and ANTON DOHRN from Woods Hole, Massachusetts, to Long Island Sound during the period from 22 January 1946 to 5 January 1947. Bathythermograms and surface salinity samples were obtained every fifteen minutes en route, and at less frequent intervals hydrographic stations were occupied, consisting of temperature and salinity readings at about five depth intervals between the surface and bottom. Figure 1 shows the area under consideration and a typical cruise plan, which, with only minor variations, was followed throughout the investigation.

Particular attention will be directed toward the description of temperature, salinity and density, including vertical and horizontal gradients and seasonal changes. In addition, an analysis will be presented of the tides, currents, diffusion processes and meteorological phenomena that are responsible for the observed salinity and temperature distribution.

From time to time reference will be made to previous studies in the area. The most comprehensive of these surveys was described by Galtsoff and Loosanoff (2), who recorded the surface and bottom temperature and salinity at numerous stations throughout Long Island Sound on three cruises in May-June, August-September and December 1935. Prytherch (3) obtained continuous thermograph records and many salinity observations in the vicinity of Milford, Connecticut, during three summer periods and also made detailed studies of tides and currents. These and other records will be utilized in later sections of the report.

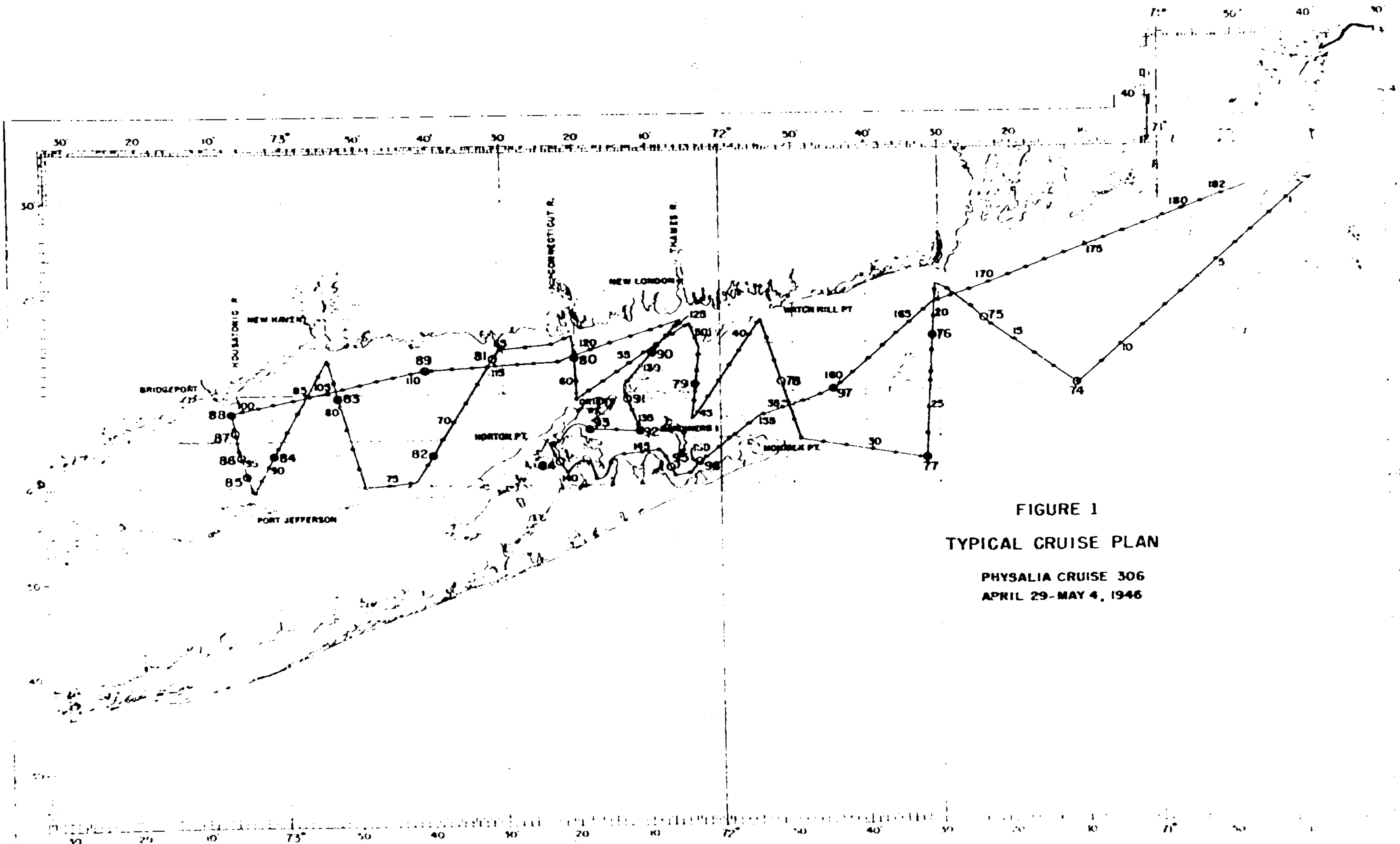


FIGURE 1

TYPICAL CRUISE PLAN

PHYSALIA CRUISE 306
APRIL 29-MAY 4, 1946

DISTRIBUTION OF TEMPERATURE, SALINITY AND DENSITY

The waters of the Long Island and Block Island Sounds are derived by admixture of saline waters from offshore with the fresh water of coastal drainage. Previous studies have shown the existence of a slow, southwesterly drift of water along the continental shelf. Part of this water is diverted into the Sounds, particularly near the bottom. As it moves into the shallow coastal zone it is progressively freshened by mixing with the products of river drainage. The inflow of saline water near the bottom is balanced by an outflow of fresher surface water which passes out of Block Island Sound near Montauk Point and becomes part of the coastwise current.

The temperature and salinity distribution in this area therefore is the result of the complicated interaction of currents and the mixing processes generated by tides and winds, combined with the alterations produced by meteorological effects at the surface. This section of the report will describe the observed temperature and salinity distribution and will explain it qualitatively in terms of the processes that have been outlined.

Horizontal distribution at the surface

Figures 2 to 19 show the observed temperature and salinity distribution at the surface. The highest salinities are found in the area between Block Island and Marthas Vineyard. They are more or less typical of the salinity of the open water of the continental shelf. To the westward, between Montauk Point

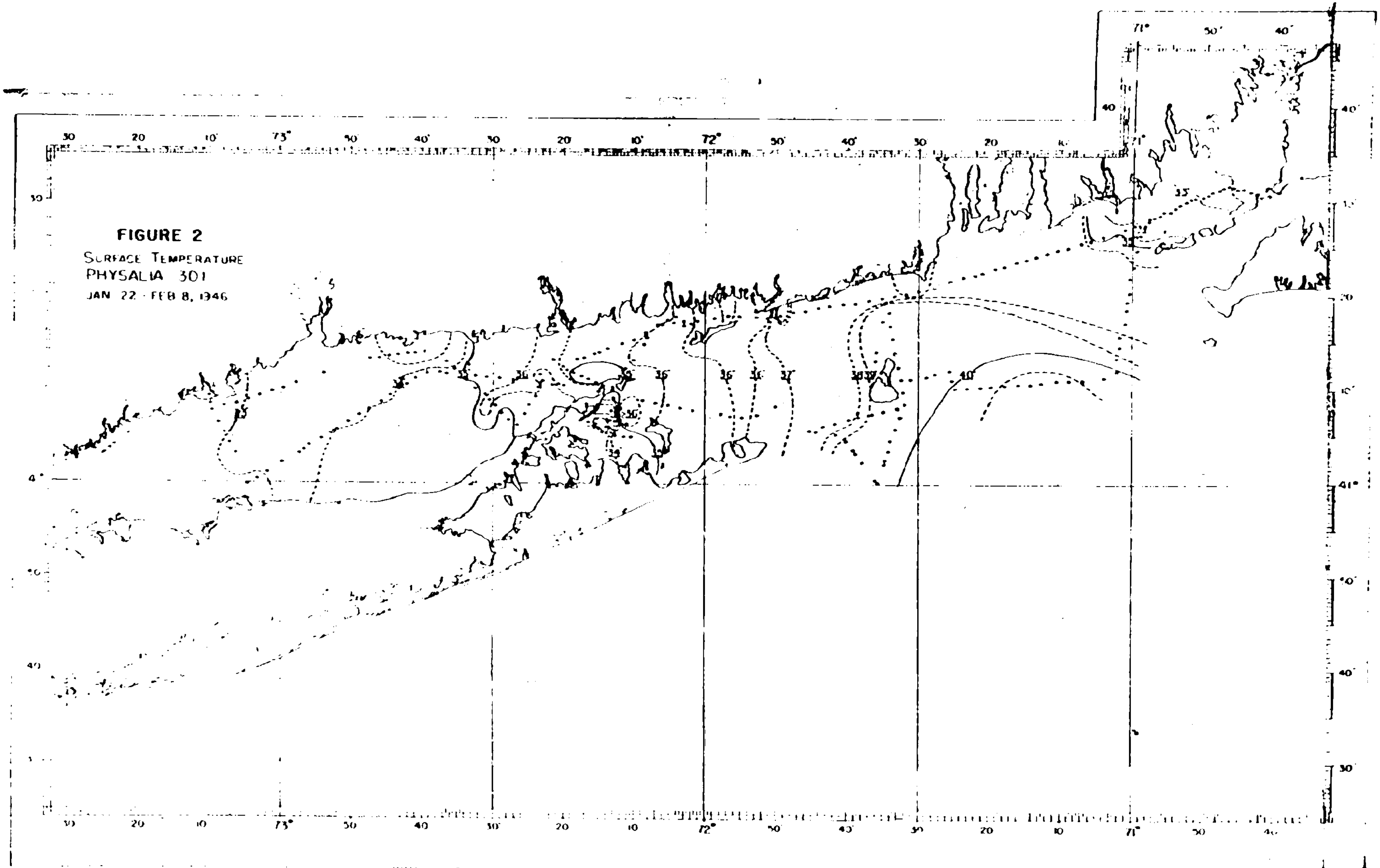


FIGURE 2

SURFACE TEMPERATURE
PHYSALIA 301
JAN 22 - FEB 8, 1946

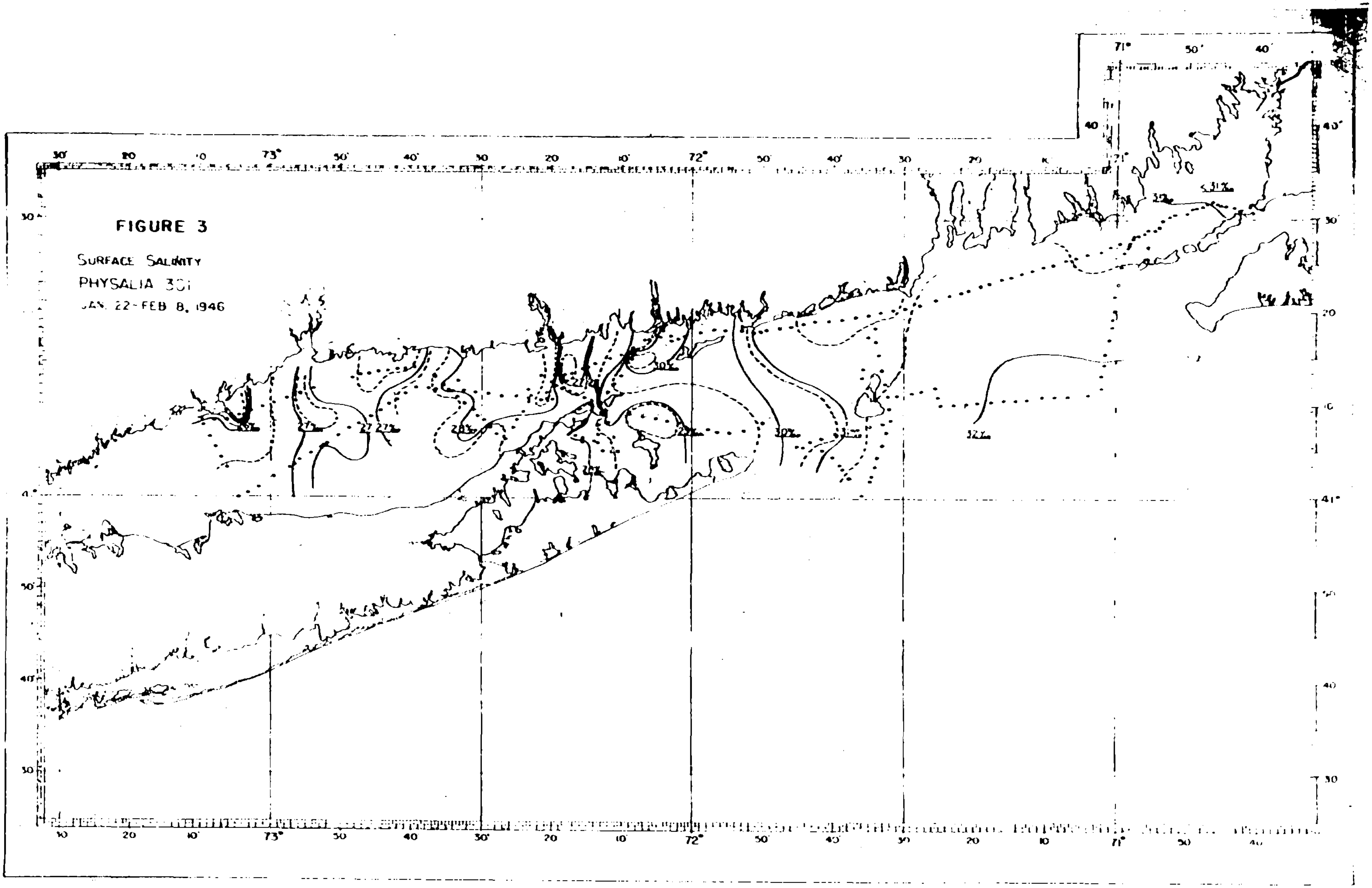


FIGURE 3
SURFACE SALINITY
PHYSALIA 301
JAN. 22-FEB 8, 1946
73°
72°
71°
41°
30‰
32‰
31‰

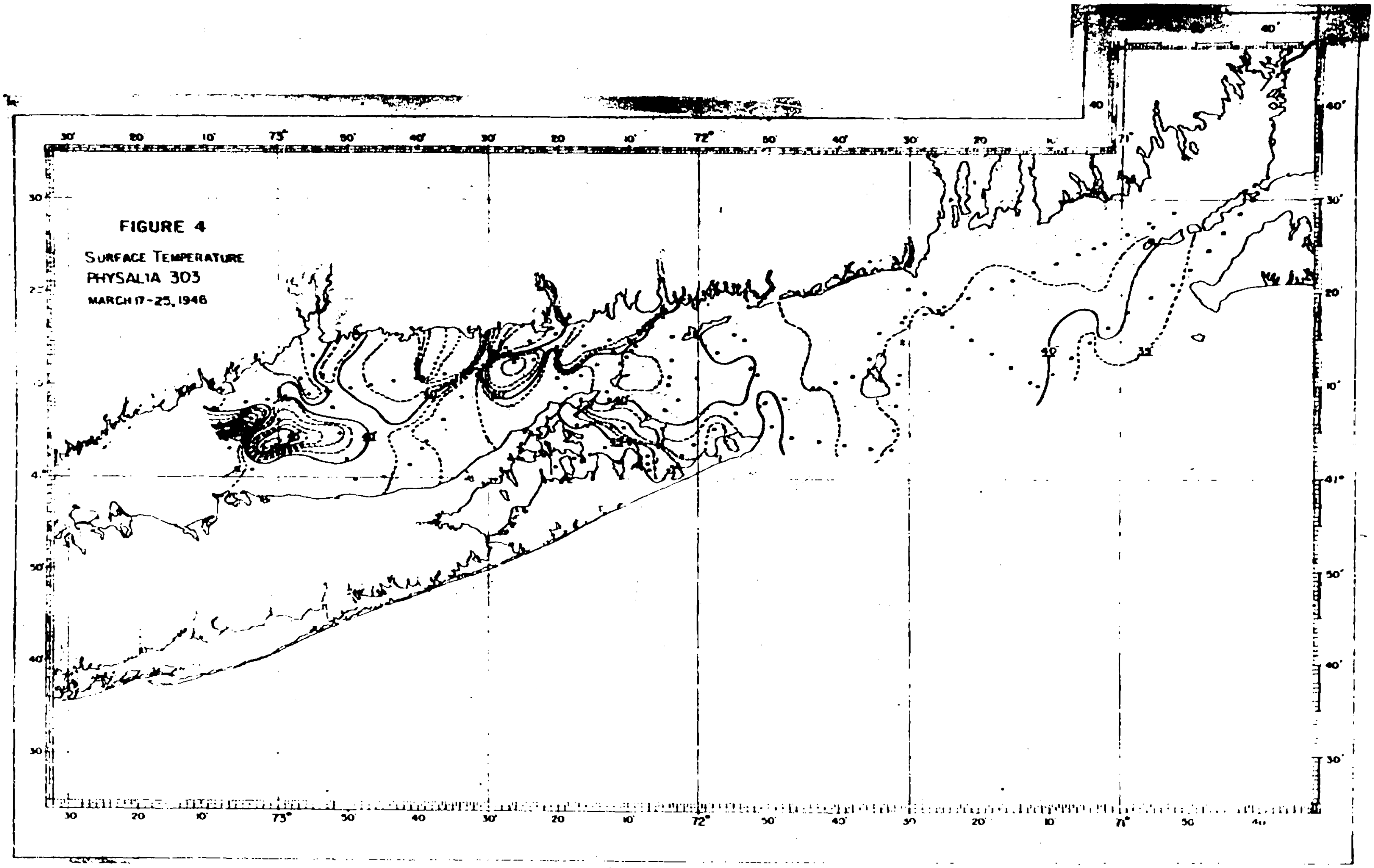


FIGURE 4

SURFACE TEMPERATURE
PHYSALIA 303
MARCH 17-25, 1948

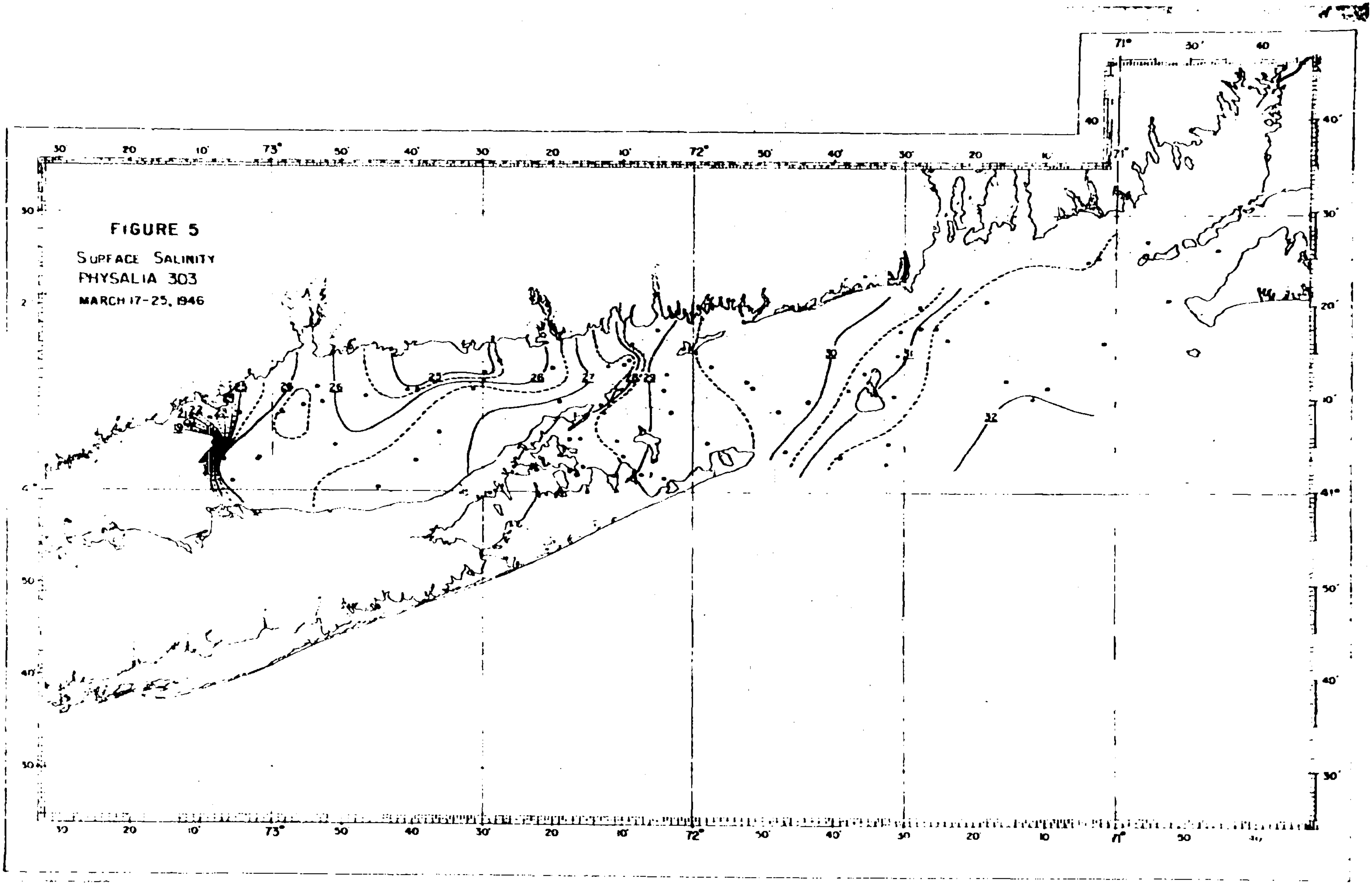


FIGURE 5

SURFACE SALINITY

PHYSALIA 303

MARCH 17-25, 1946

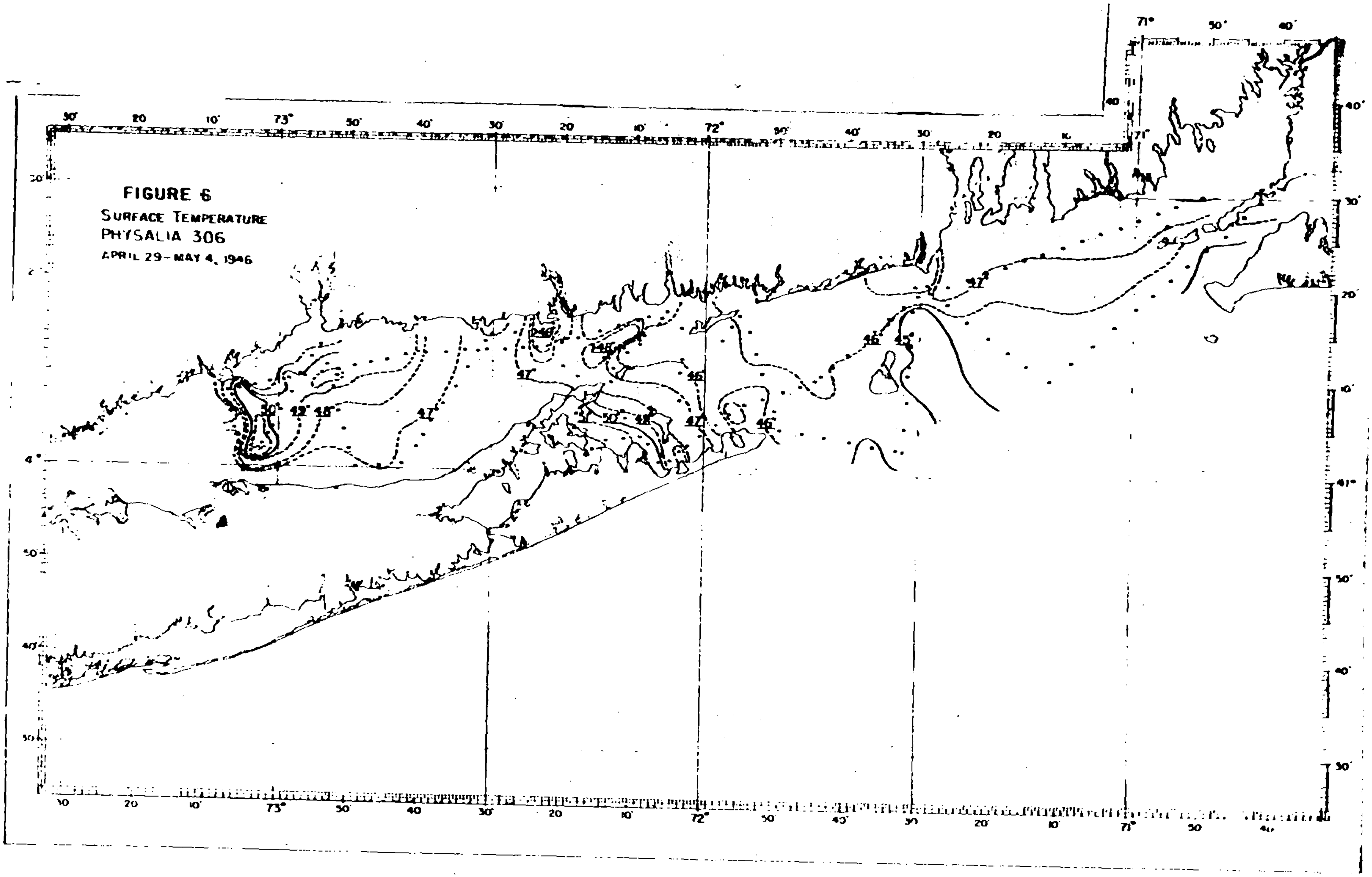


FIGURE 6
SURFACE TEMPERATURE
PHYSALIA 306
APRIL 29–MAY 4, 1946

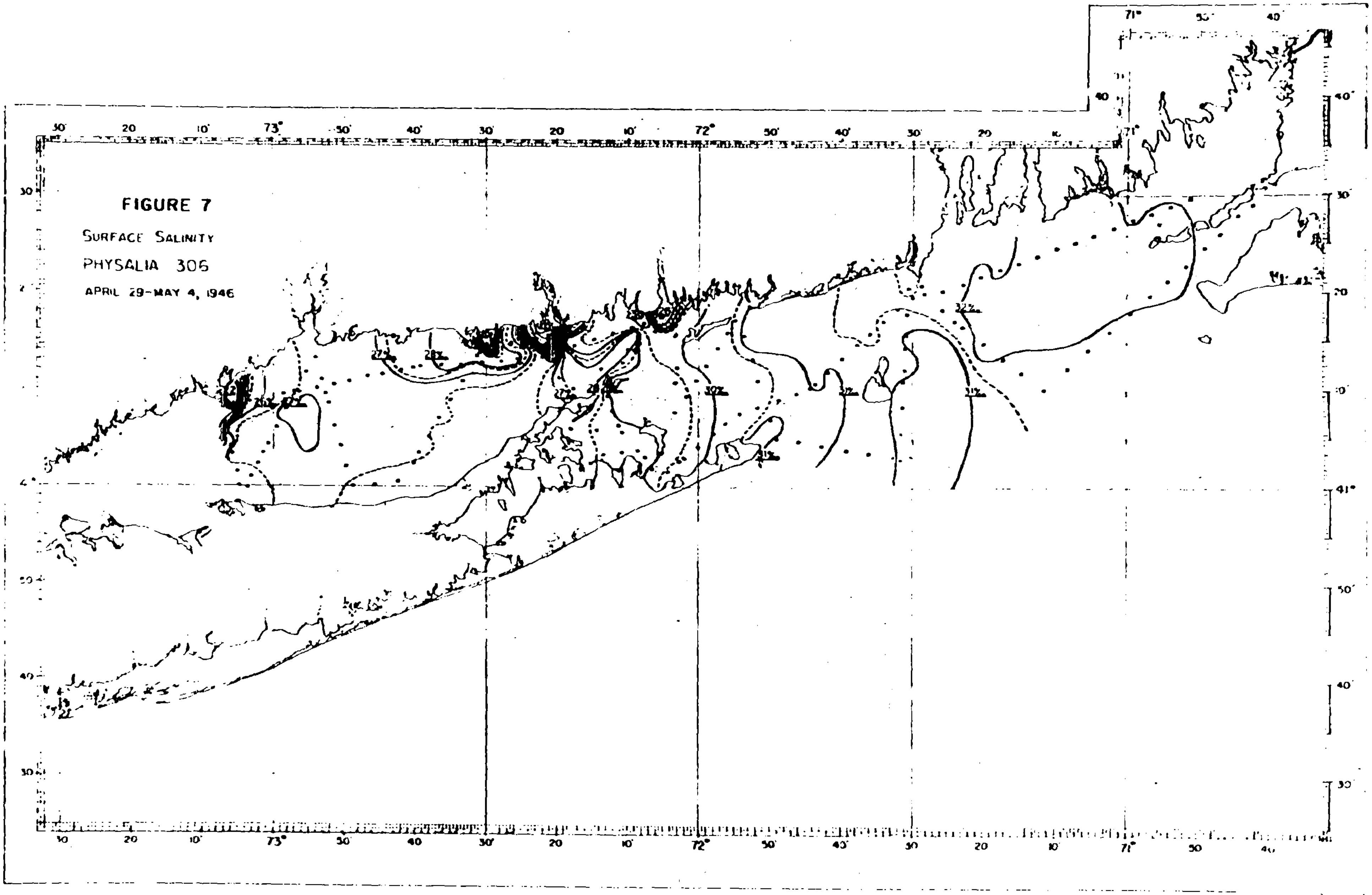


FIGURE 7

SURFACE SALINITY

PHYSALIA 306

APRIL 29-MAY 4, 1946

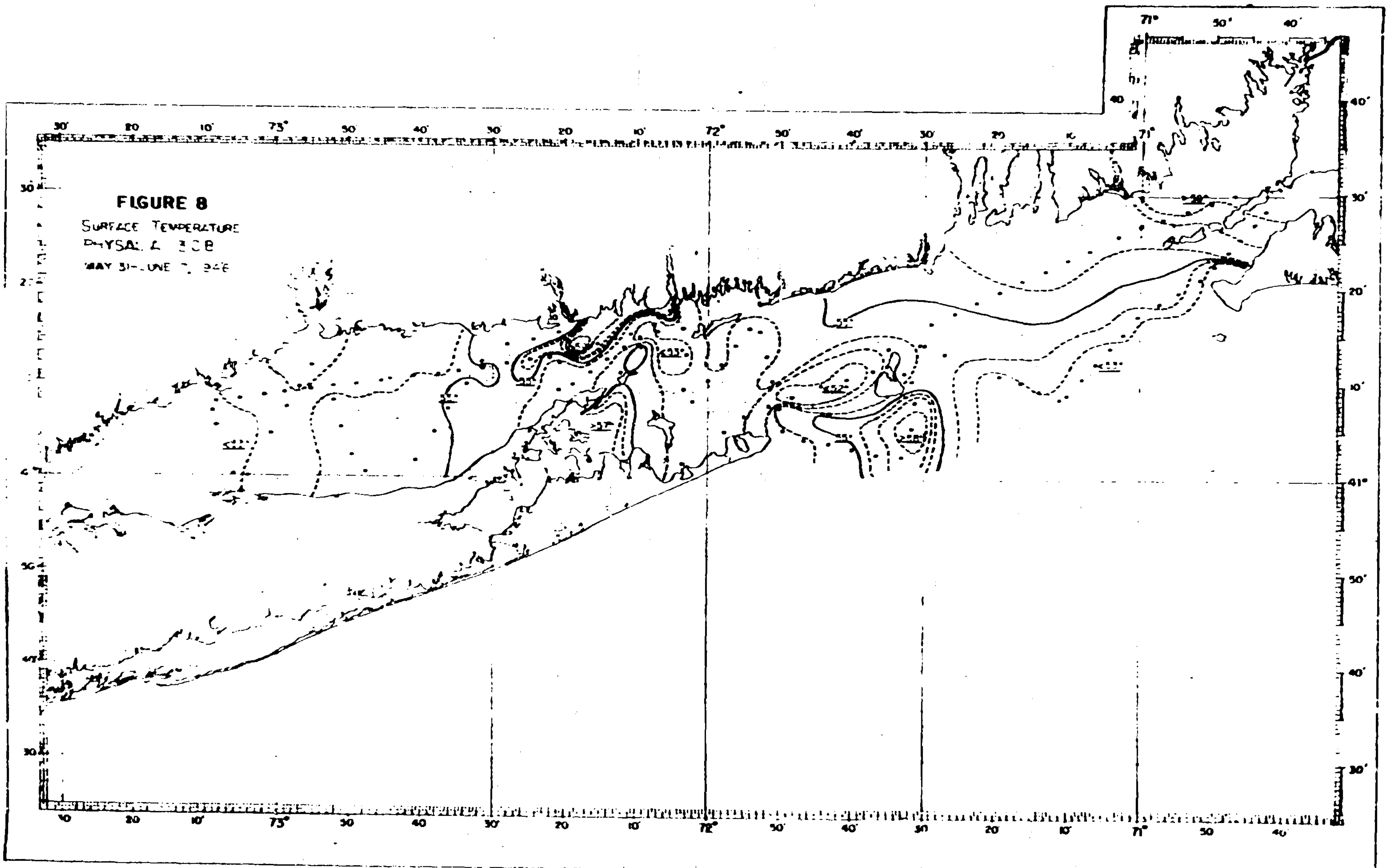


FIGURE 8
SURFACE TEMPERATURE
PHYSALIA 308
MAY 31–JUNE 7, 1948

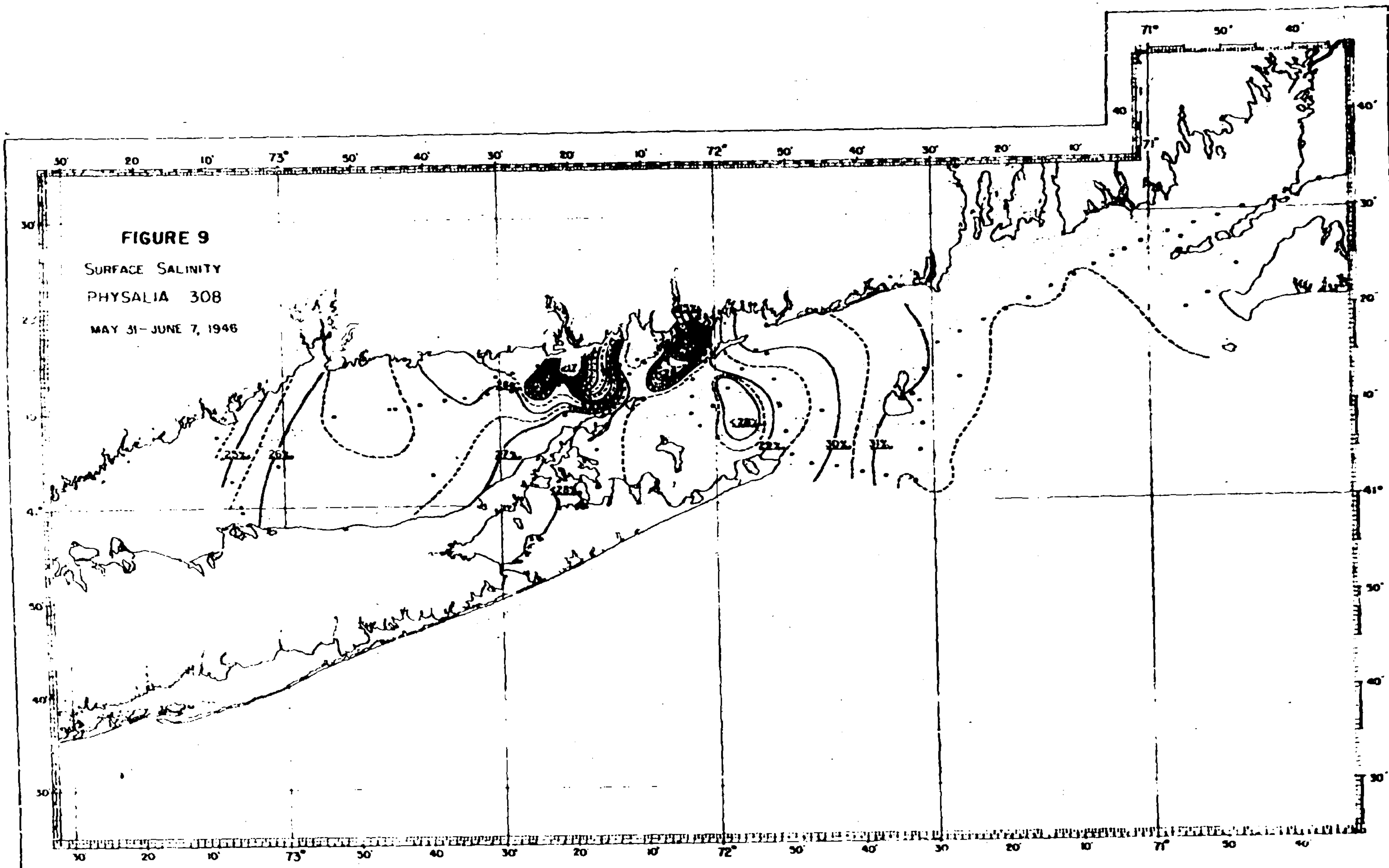


FIGURE 9

SURFACE SALINITY

PHYSALIA 308

MAY 31 - JUNE 7, 1946

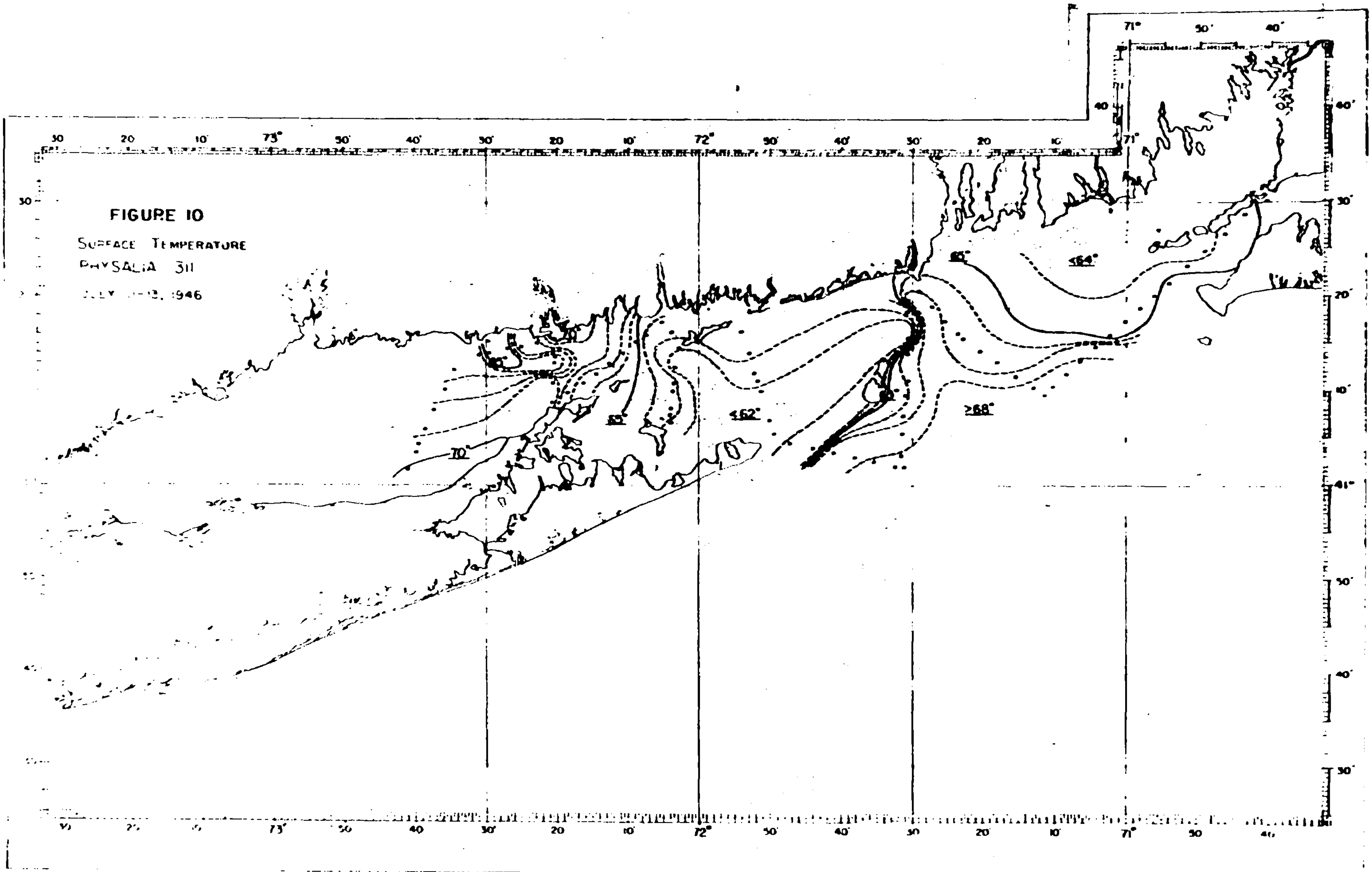


FIGURE 10

SURFACE TEMPERATURE

PHYSALIA 311

JULY [illegible], 1946

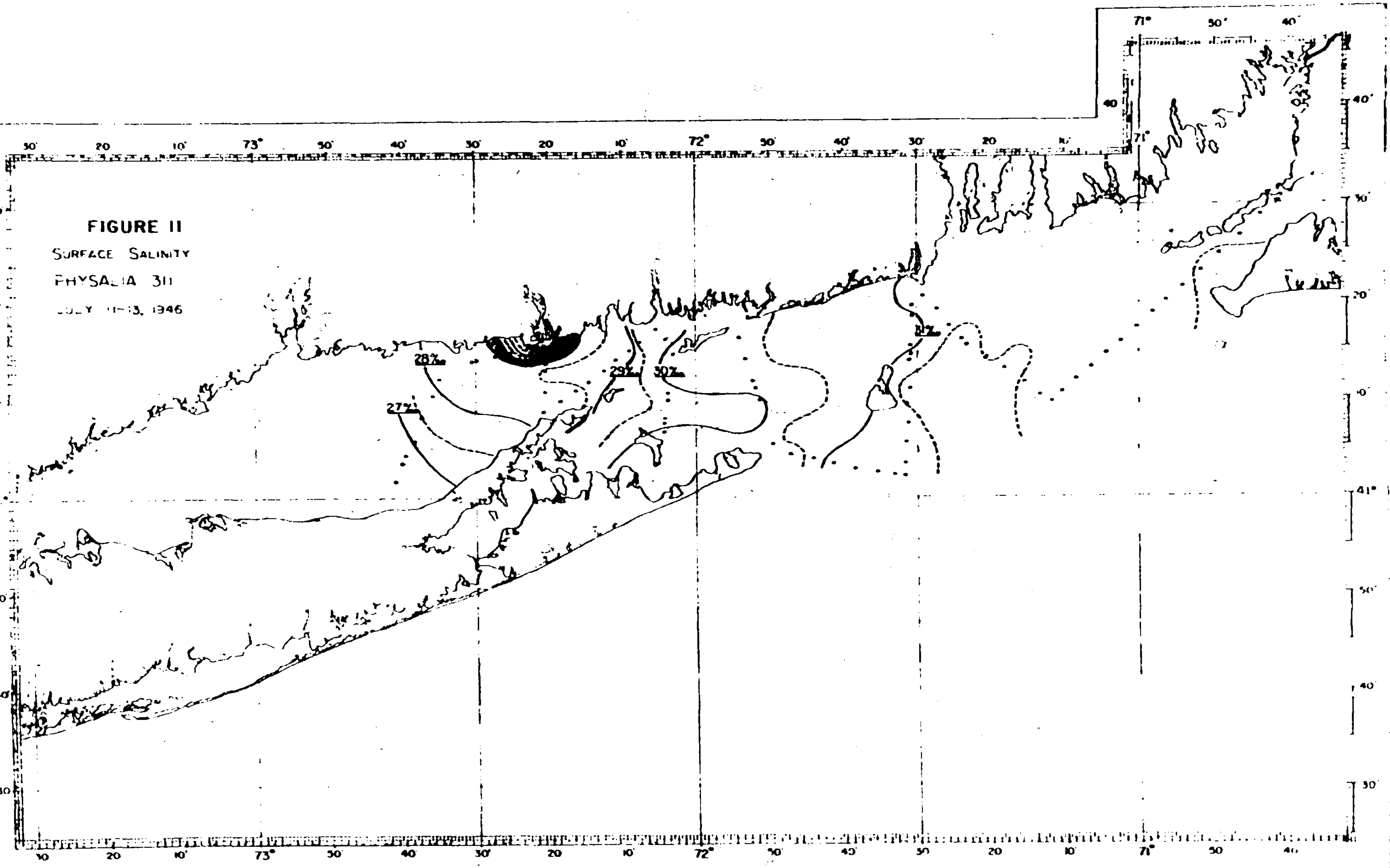


FIGURE II

SURFACE SALINITY

PHYSALIA 311

JULY 11-13, 1946

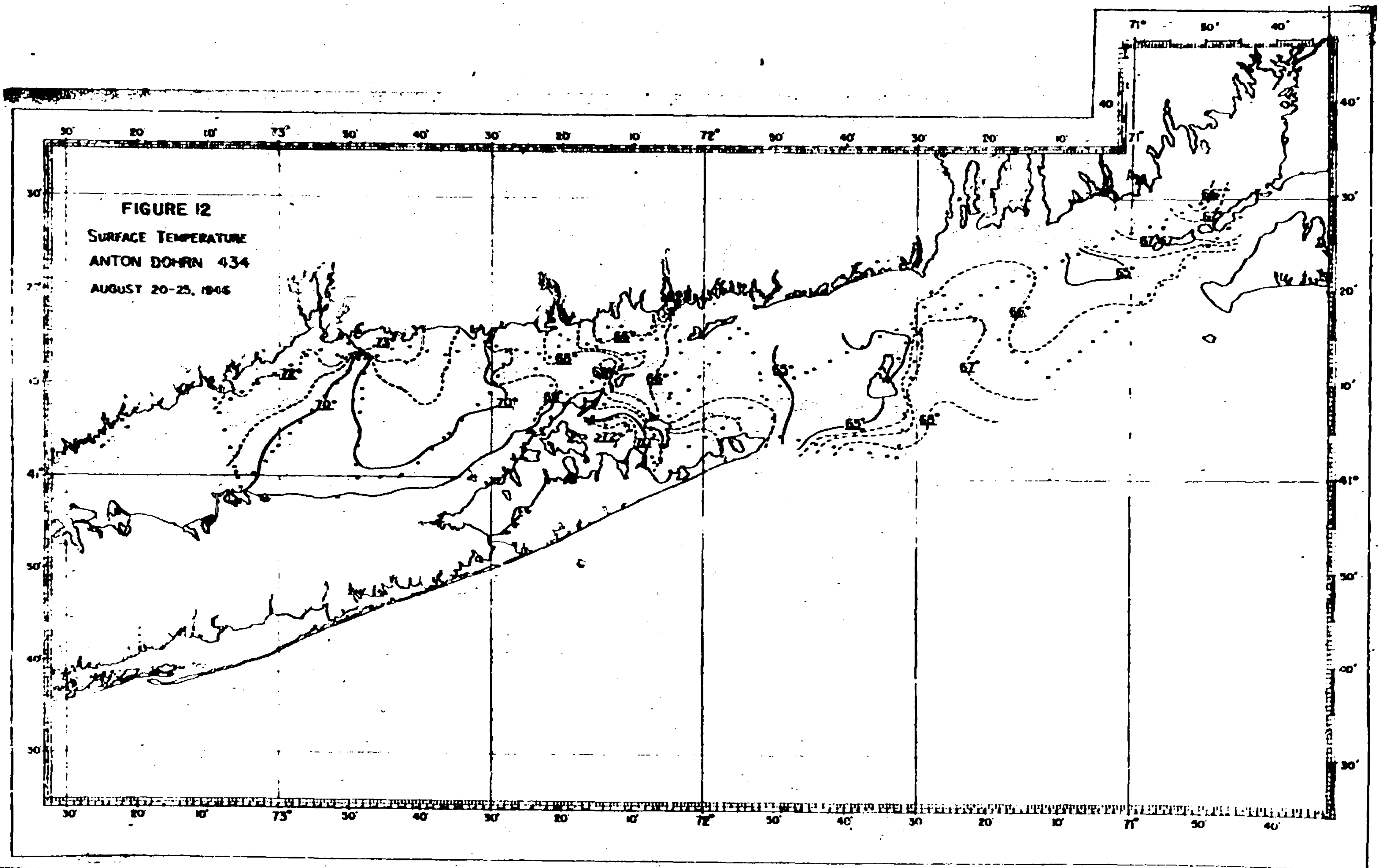


FIGURE 12

SURFACE TEMPERATURE

ANTON DOHRN 434

AUGUST 20-25, 1946

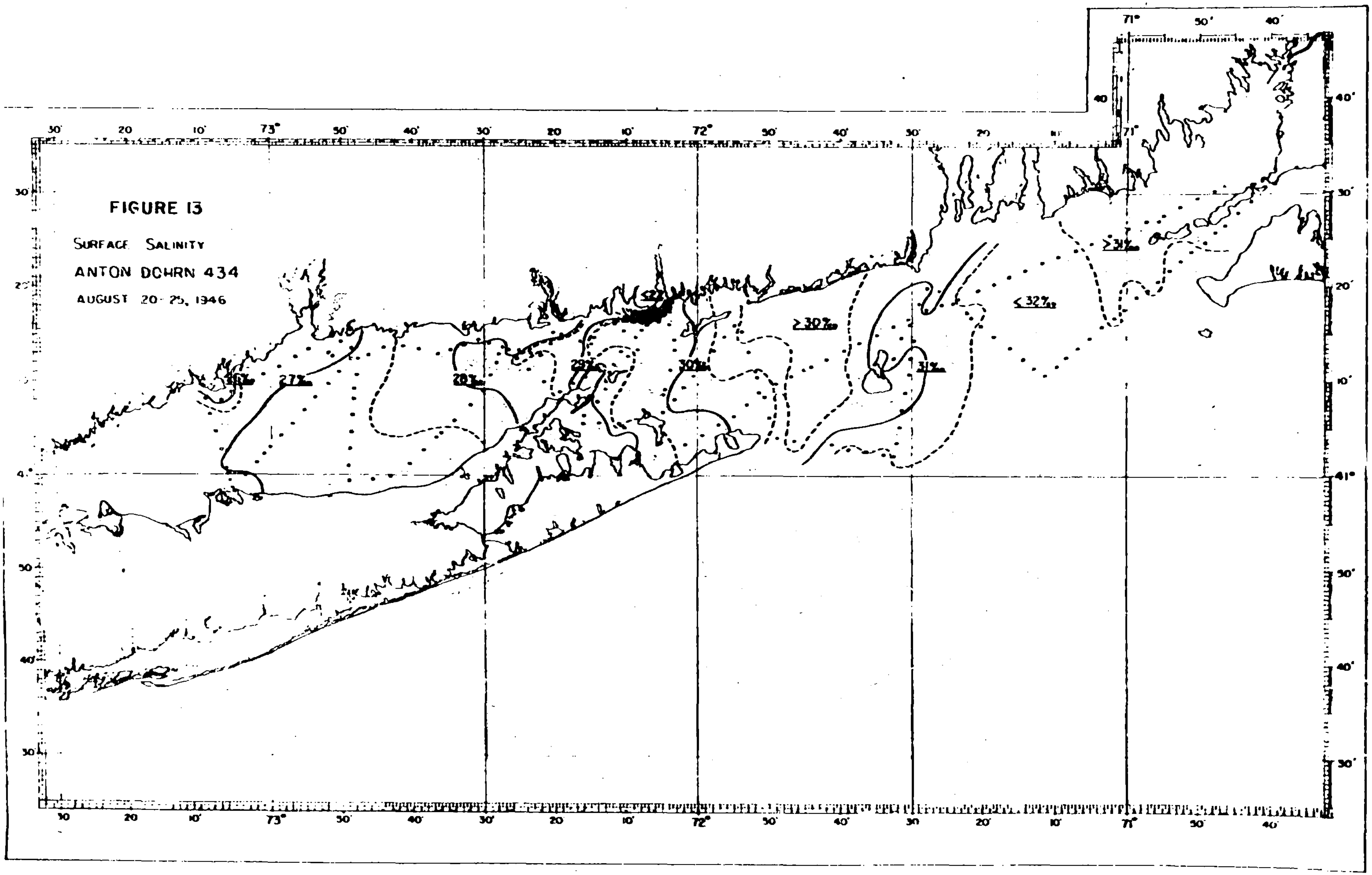


FIGURE 13

SURFACE SALINITY

ANTON DOHRN 434

AUGUST 20-25, 1946

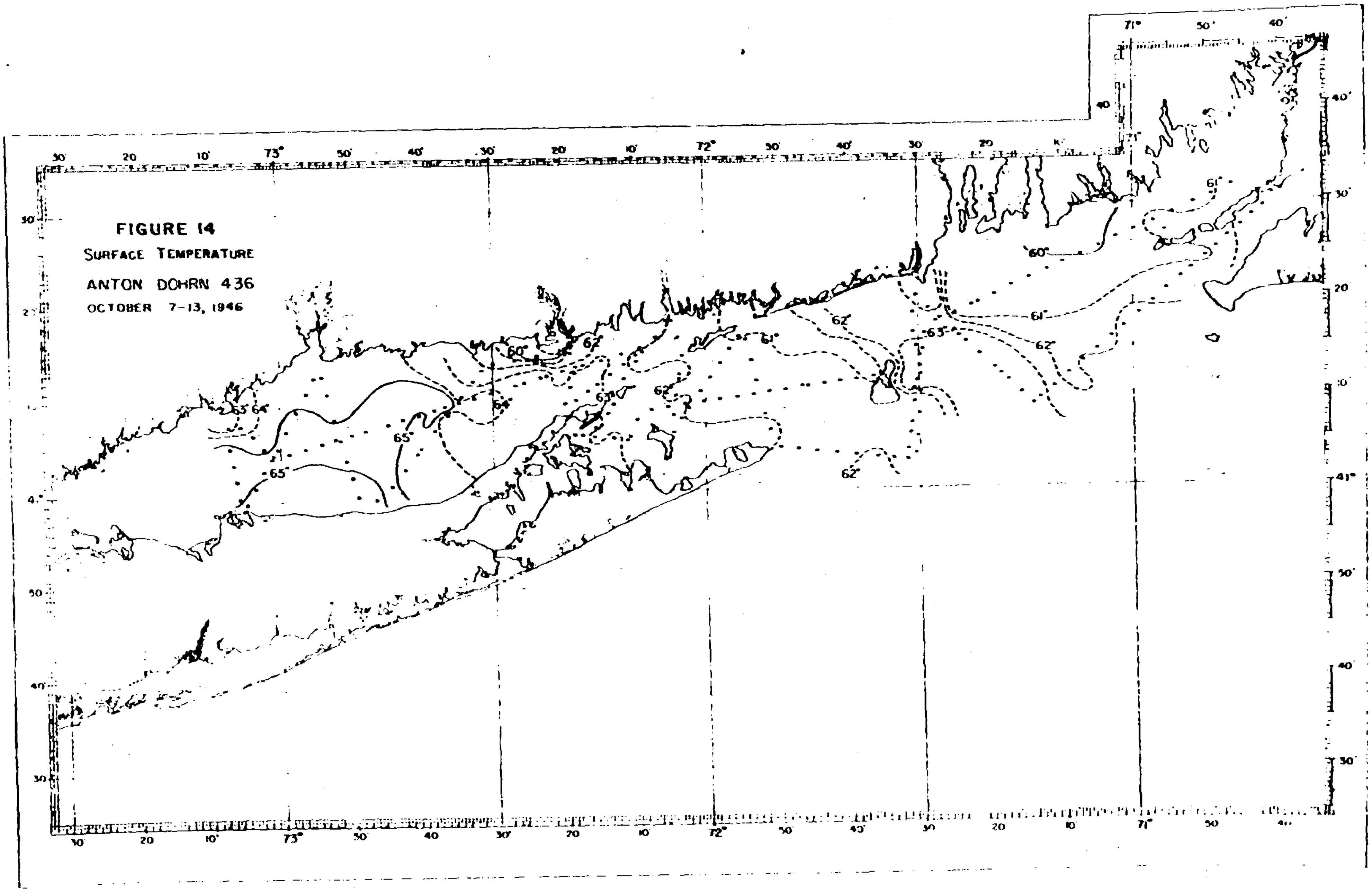


FIGURE 14

SURFACE TEMPERATURE

ANTON DOHRN 436

OCTOBER 7-13, 1946

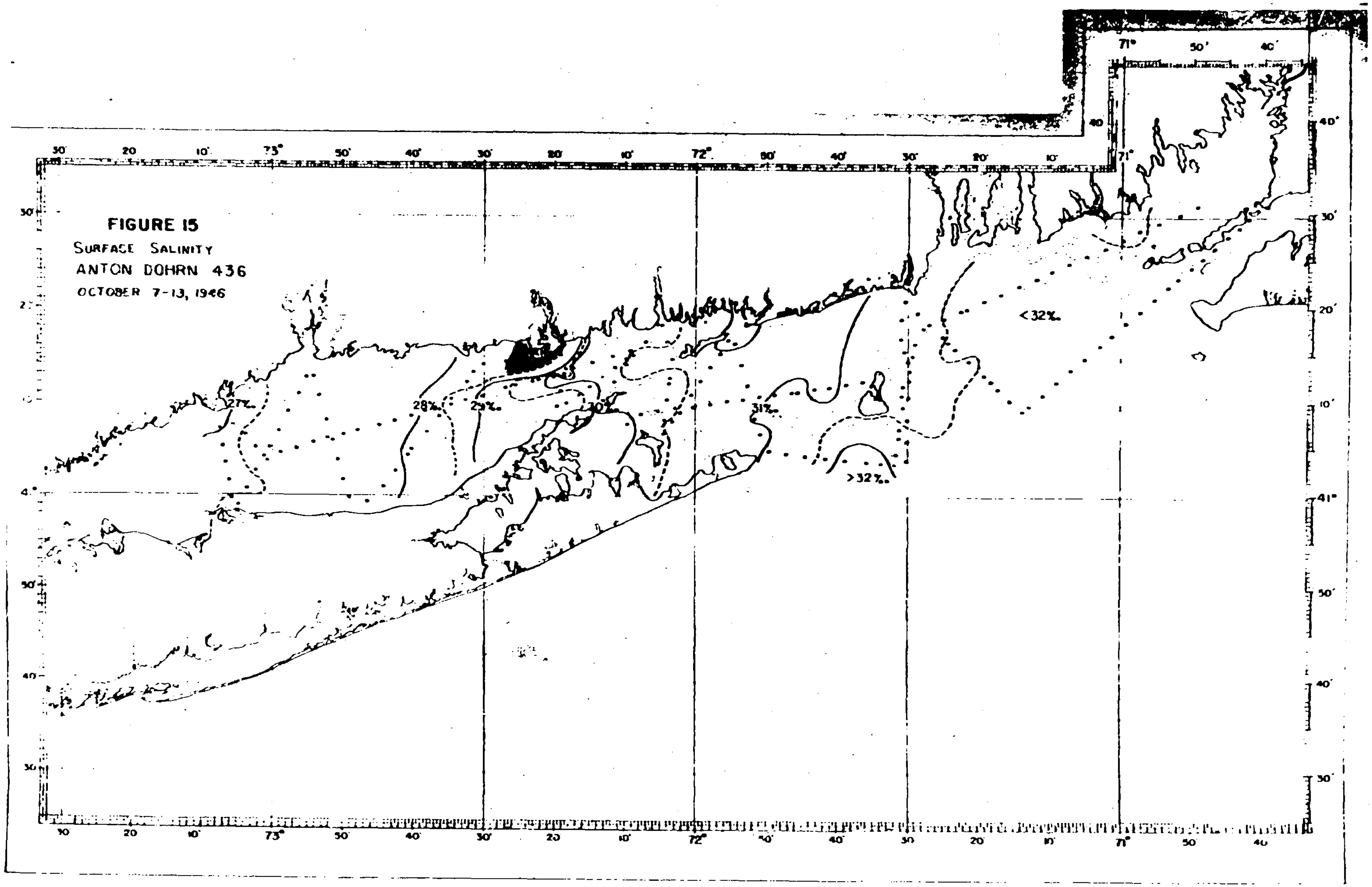


FIGURE 15

SURFACE SALINITY

ANTON DOHRN 436

OCTOBER 7-13, 1946

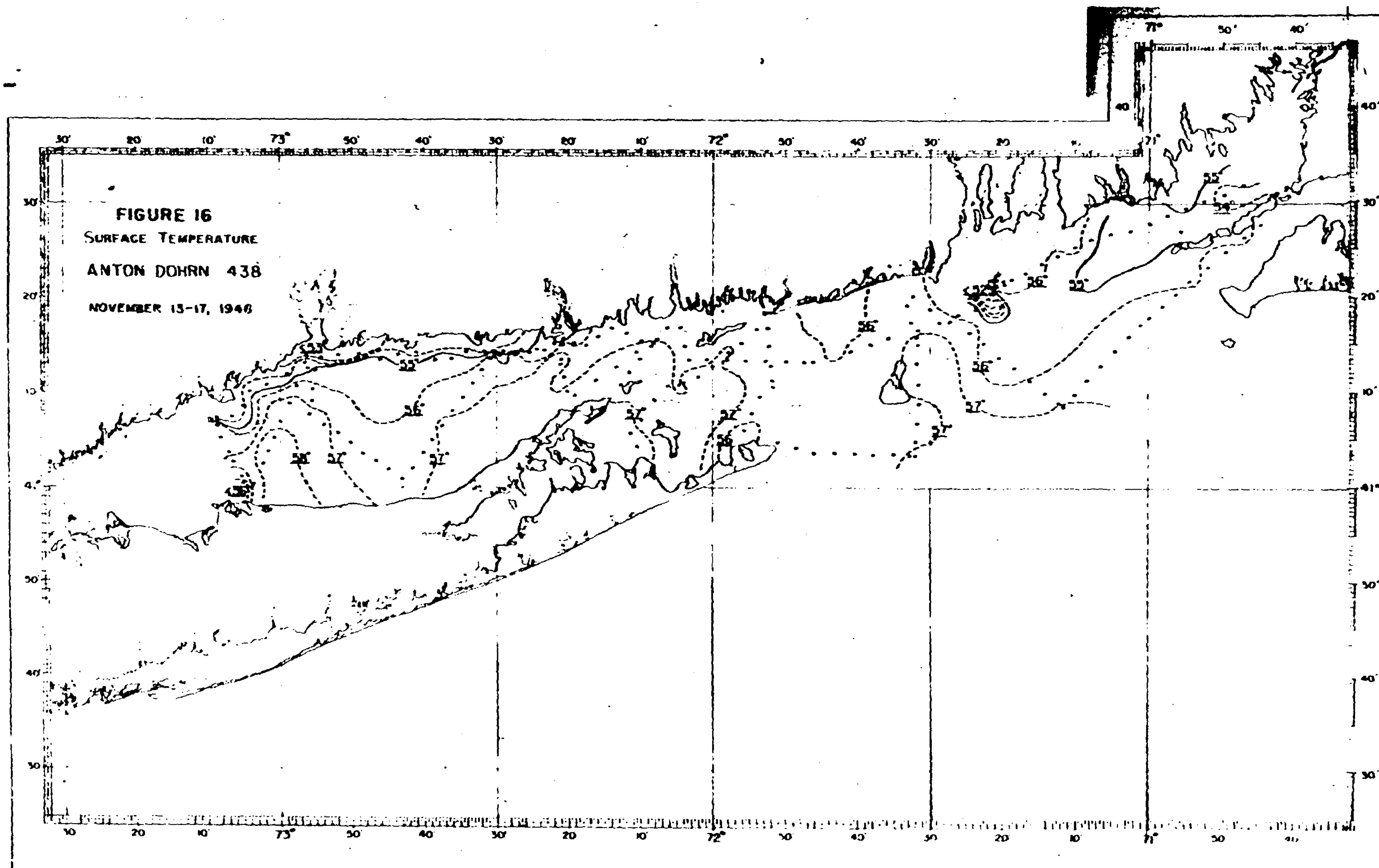


FIGURE 16

SURFACE TEMPERATURE

ANTON DOHRN 438

NOVEMBER 13-17, 1948

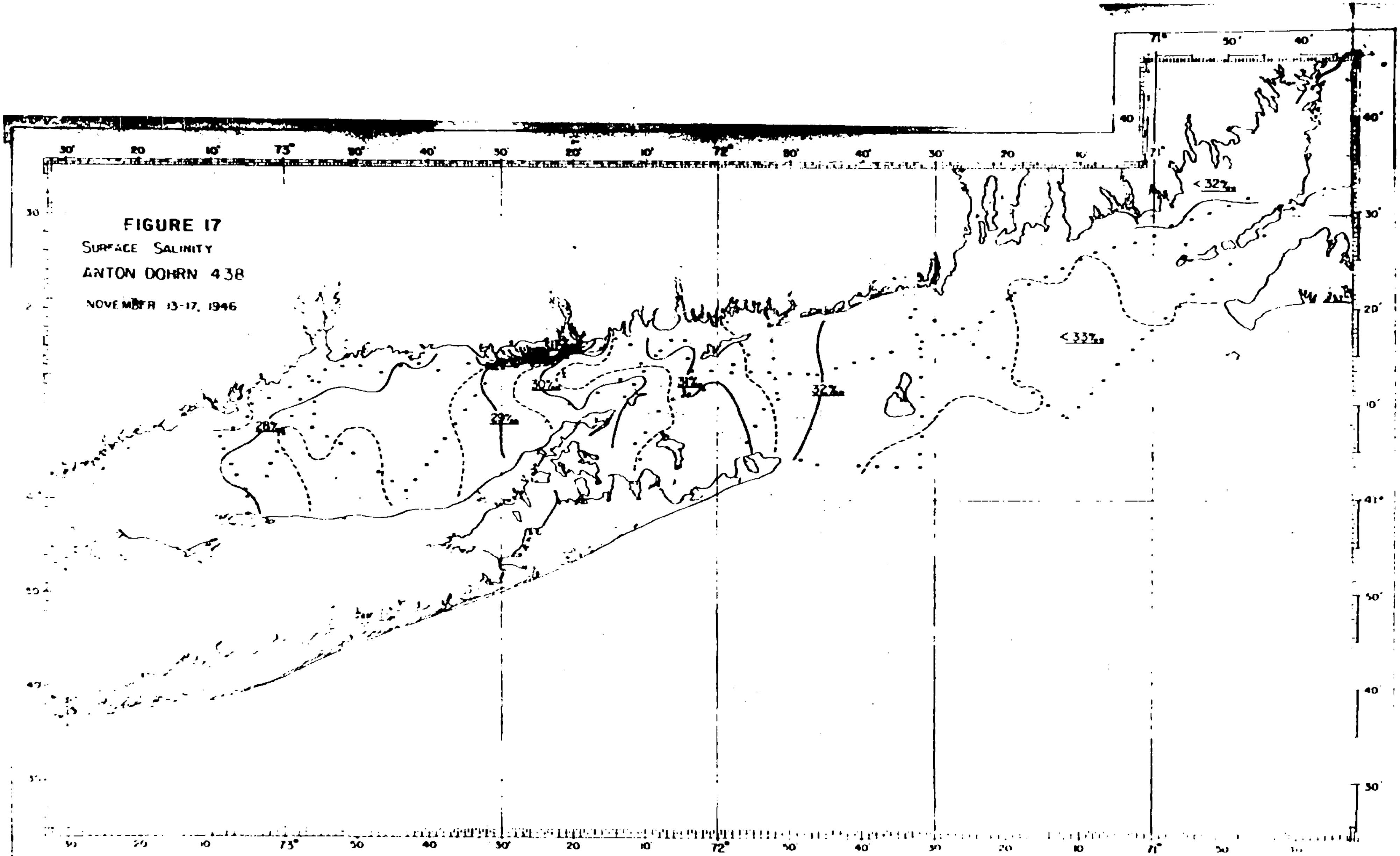


FIGURE 17
SURFACE SALINITY
ANTON DOHRN 438
NOVEMBER 13-17, 1946

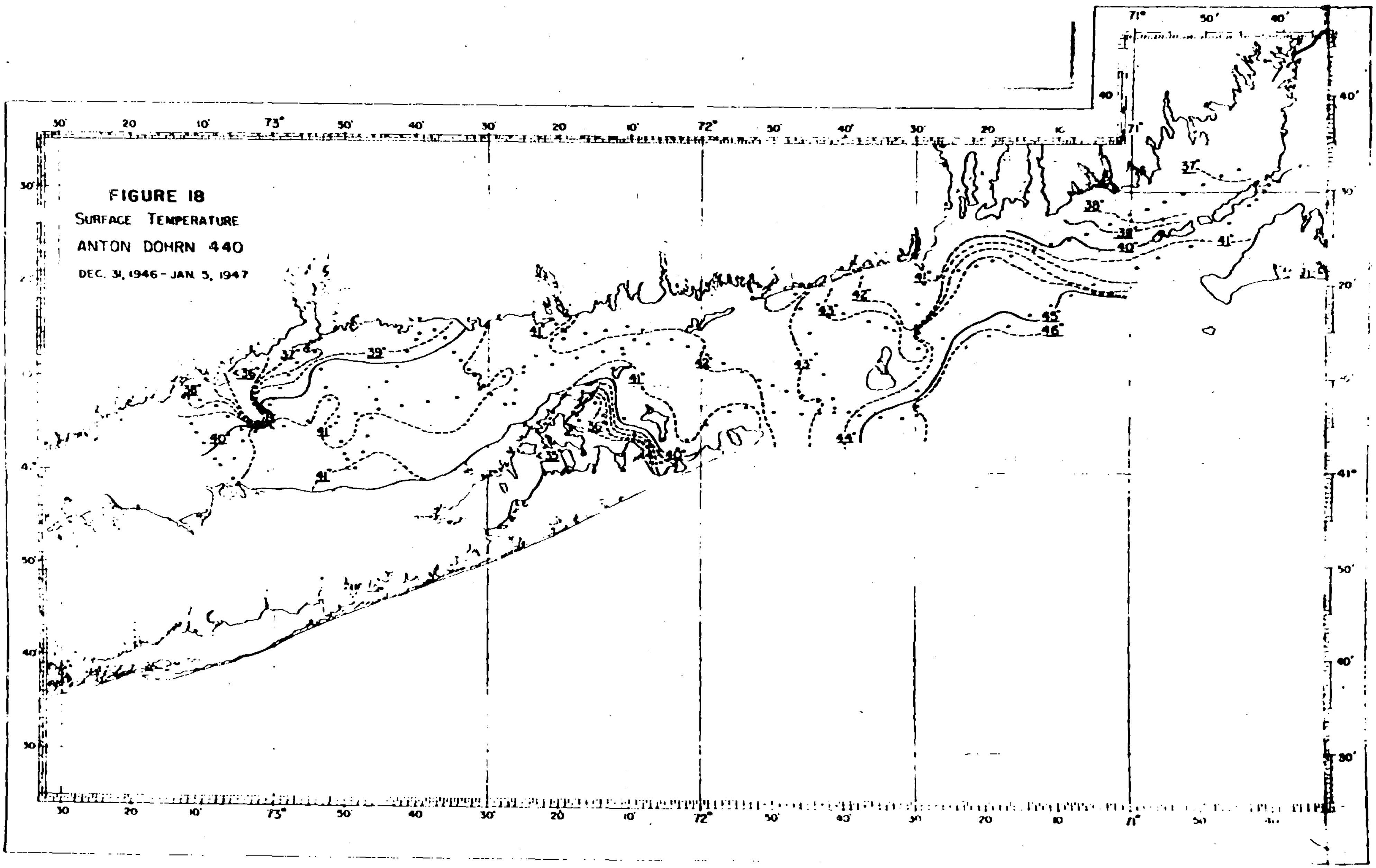


FIGURE 18

SURFACE TEMPERATURE

ANTON DOHRN 440

DEC. 31, 1946 - JAN. 5, 1947

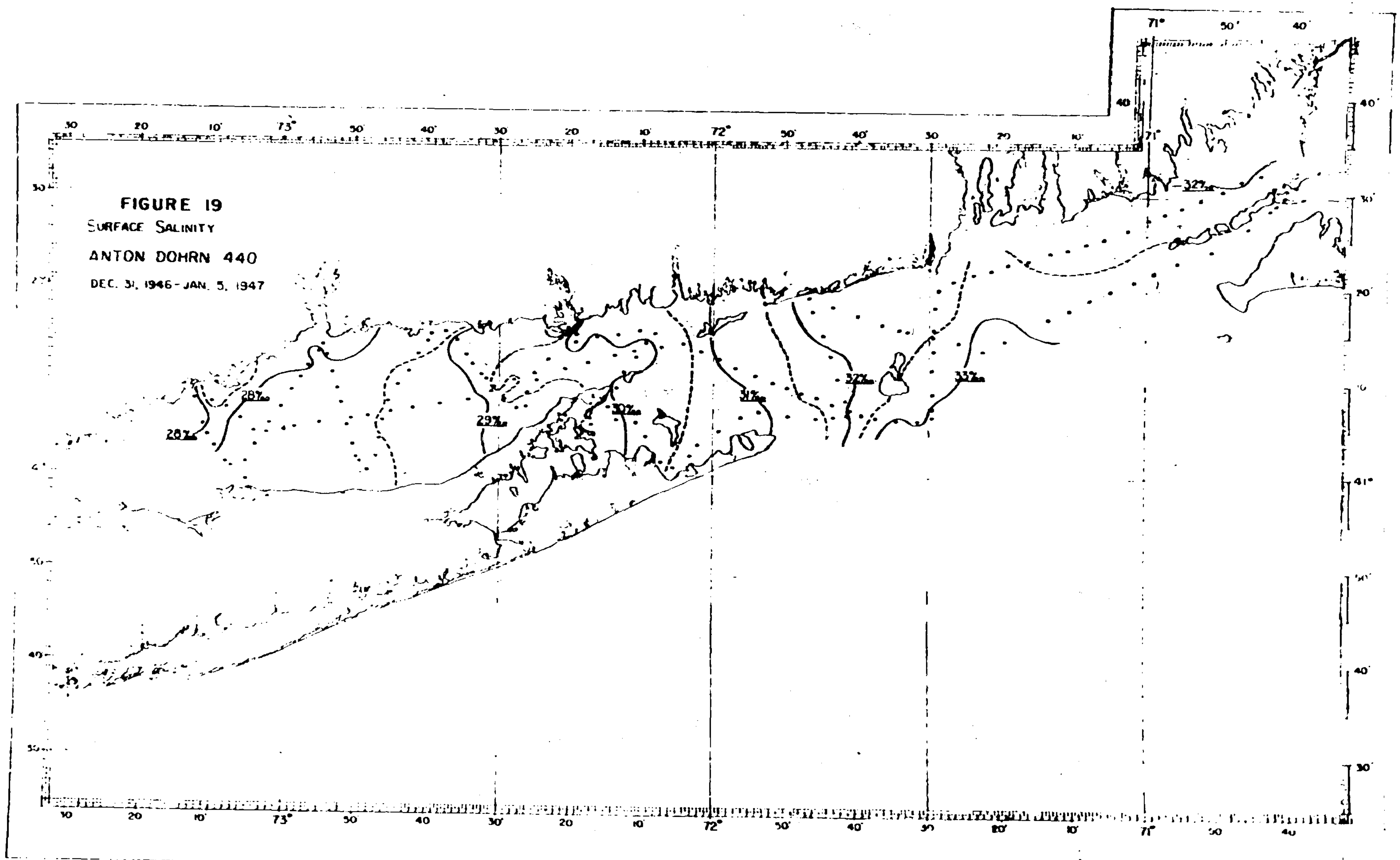


FIGURE 19
SURFACE SALINITY
ANTON DOHRN 440
DEC. 31, 1946 - JAN. 5, 1947

and Block Island, the more complicated salinity structure shows that a considerable quantity of relatively fresh water from Long Island Sound drains out around Montauk Point. In some cases this drainage is revealed simply by a bending of the isohalines around the Point and a general increase in salinity toward the east and north. In other cases there appear to be discrete masses of low salinity water traversing the area.

In the semi-enclosed basins of Long Island Sound and Gardiners Bay, and to a lesser extent in Buzzards Bay and Vineyard Sound, the salinity decreases from the entrances toward the inner portions as a result of progressive dilution by river drainage. The charts show examples of various stages of the process of dispersal of river water, including pockets of very fresh water at the immediate mouths of the rivers and larger and more diffuse patches that have been carried away by tidal drift. Occasional more detailed surveys have demonstrated a highly irregular distribution of salinity within the patches, often consisting of alterating streaks of low and high salinity, which generally are demarked by visible rips on the surface as well as by a change in the turbidity of the water. Such structures move continually with the tide and are largely dissipated within a few hours. A second crossing of such an area a few hours later may yield a very different picture of salinity distribution. However, the frequency with which freshwater patches were encountered shows that they are almost always present somewhere within ten or fifteen miles of a large river.

Galtsoff and Loosanoff (2) reported a seasonal variation in salinity, the largest change occurring in the western part of Long Island Sound where it reached a magnitude of two to three parts per mille, the minimum salinity occurring in spring, the maximum in autumn, corresponding to the seasonal variation in river drainage. Similar results were obtained in the present survey.

The seasonal temperature change is of course much more pronounced. It depends fundamentally on the seasonal cycle of radiation and air temperature but is considerably modified by oceanographic factors. Other things being equal, a given amount of heat transfer at the surface of the water will be most effective in changing the temperature of the whole water mass when the latter is shallow. Other important factors are tidal currents and the vertical stability of the water column, which affect the vertical transfer of heat. With a few exceptions that will be noted in passing, these processes operate so that the seasonal changes are greatest in shallow water near shore and decrease in the deeper water. The difference between midsummer and midwinter temperatures is of the order of 25° to 30° off Block Island, ranges up to 35° in most of the coastal zone, and may be as much as 45° in harbors and inlets according to data published by Prytheroh (3) and Riley (4).

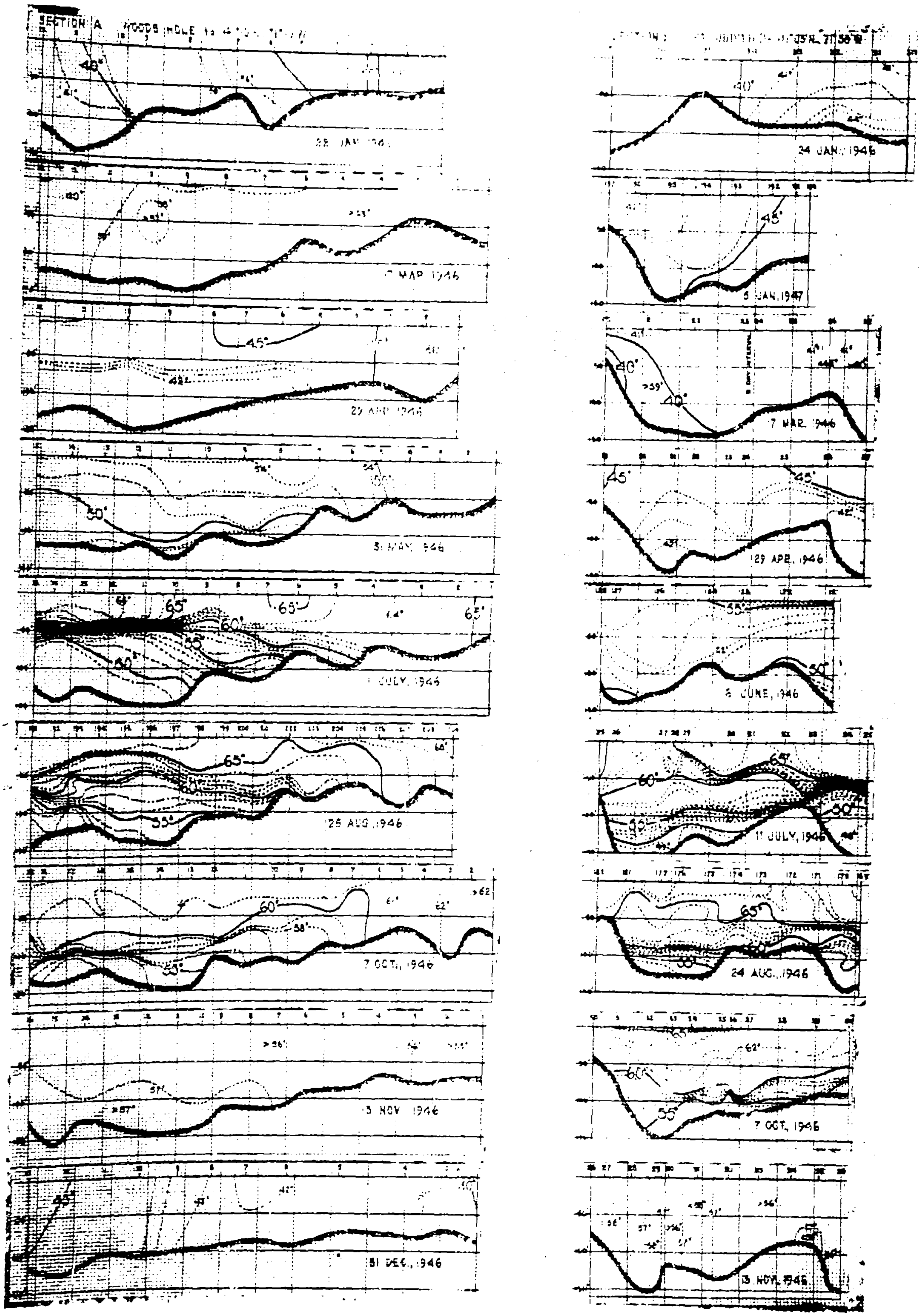
Thus in midwinter the surface temperature is 40°F or more offshore and decreases toward the freezing point in inshore waters. Conversely summer temperatures in the coastal waters are generally a few degrees higher than in the outer part of the area. However, it will be noted that the minimum summer temperatures are obtained neither in the coastal region nor the part farthest offshore but in an intermediate zone about ten miles from the coast. This results from the interaction of two factors working in opposite direction. Increasing depth of water provides a medium for the downward dissipation of heat entering the surface layer, but it also is accompanied by a lessening of the tidal currents that supply energy for vertical transfer. The intermediate, low-temperature zone marks the place where the combination of these two factors is optimal for transferring heat downward from the surface. Further offshore, tidal currents are not strong enough to prevent the formation of a strong vertical temperature gradient, so that the surface water is a little warmer and the bottom water much colder than in the intermediate zone.

These processes of surface heat exchange and vertical transfer largely control the horizontal variations in temperature. Later it will be shown that they are quantitatively much more important than current transport and horizontal diffusion in most of the area studied.

Finally, the charts show that localized patches of low-salinity water also have distinctive temperature characteristics. In winter they are usually colder than the surrounding water of higher salinity, and in summer they are warmer. To a slight extent this reflects the marked temperature cycles of the rivers from which the fresh water is ultimately derived. More important, however, is the fact that the patches are of limited vertical extent. Thus the vertical salinity gradient creates a thin and stable surface layer which magnifies the effects of surface heat exchange.

Vertical distribution

Figures 20 to 23 are vertical temperature sections constructed from the lines of bathythermograph lowerings made on each cruise. The positions of the sections varied slightly from one cruise to the next, but the mean positions marked in Figure 24 are sufficiently accurate for general reference. The sections serve to illustrate the details of the seasonal and regional variation in temperature and the intensity of thermal stratification, the main outlines of which have already been explained in general terms. It is apparent from the figures that temperature gradients in the Long Island and Block Island Sounds are small compared with the outside water. However, since the water is fresher at the surface than at the bottom through most of the region, the stability is slightly greater than would be indicated by temperature gradients alone. The quantity of salinity



SECTION A WOODS HOLE
28 JAN 1946
24 JAN 1946
MAR 1946
5 JAN 1947
45°
22 APR 1946
7 MAR 1946
3 MAY 1946
29 APR 1946
1 JULY 1946
6 JUNE 1946
25 AUG 1946
11 JULY 1946
7 OCT 1946
24 AUG 1946
13 NOV 1946
7 OCT 1946
31 DEC 1946
13 NOV 1946

FIGURE 20

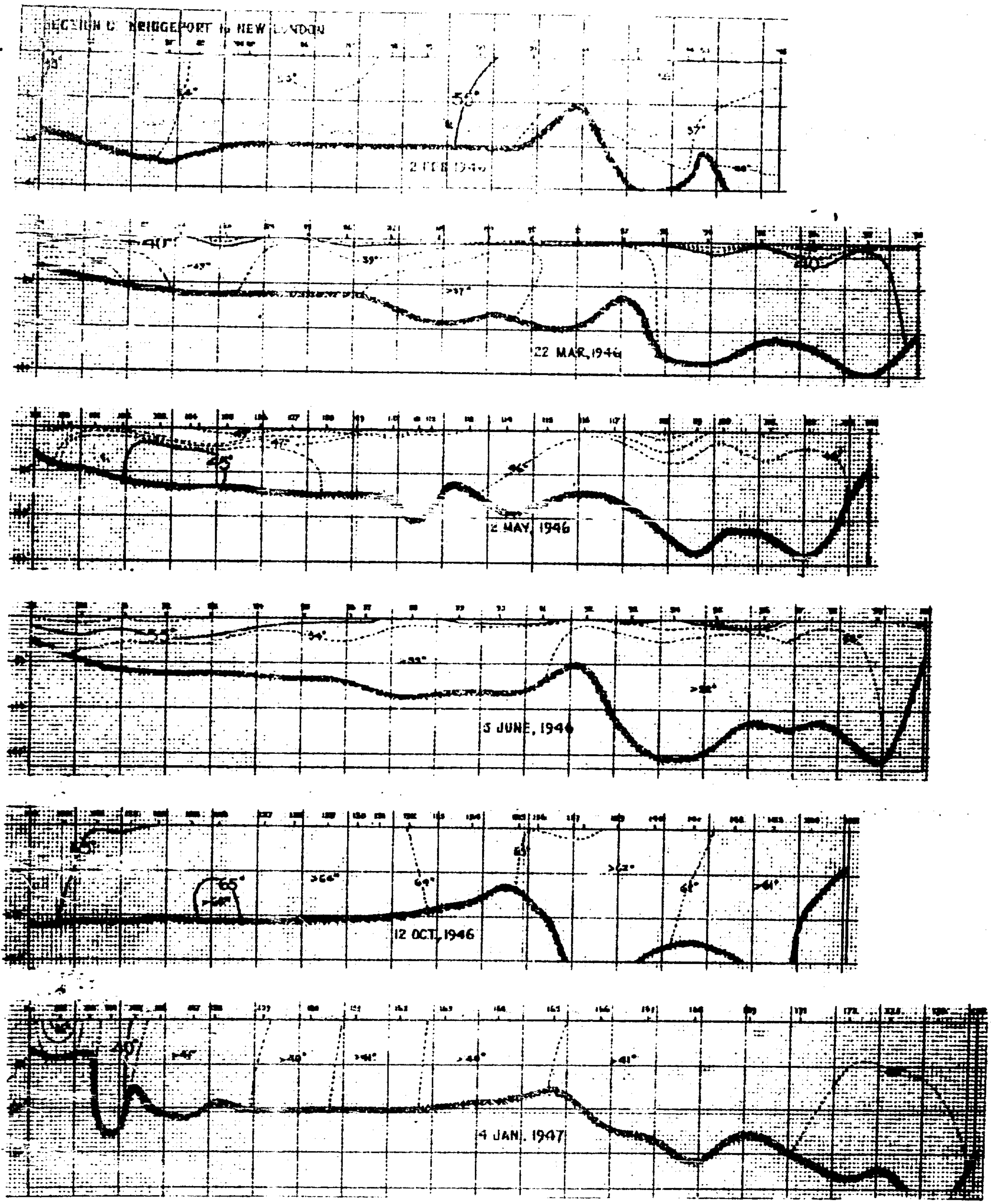


FIGURE 21

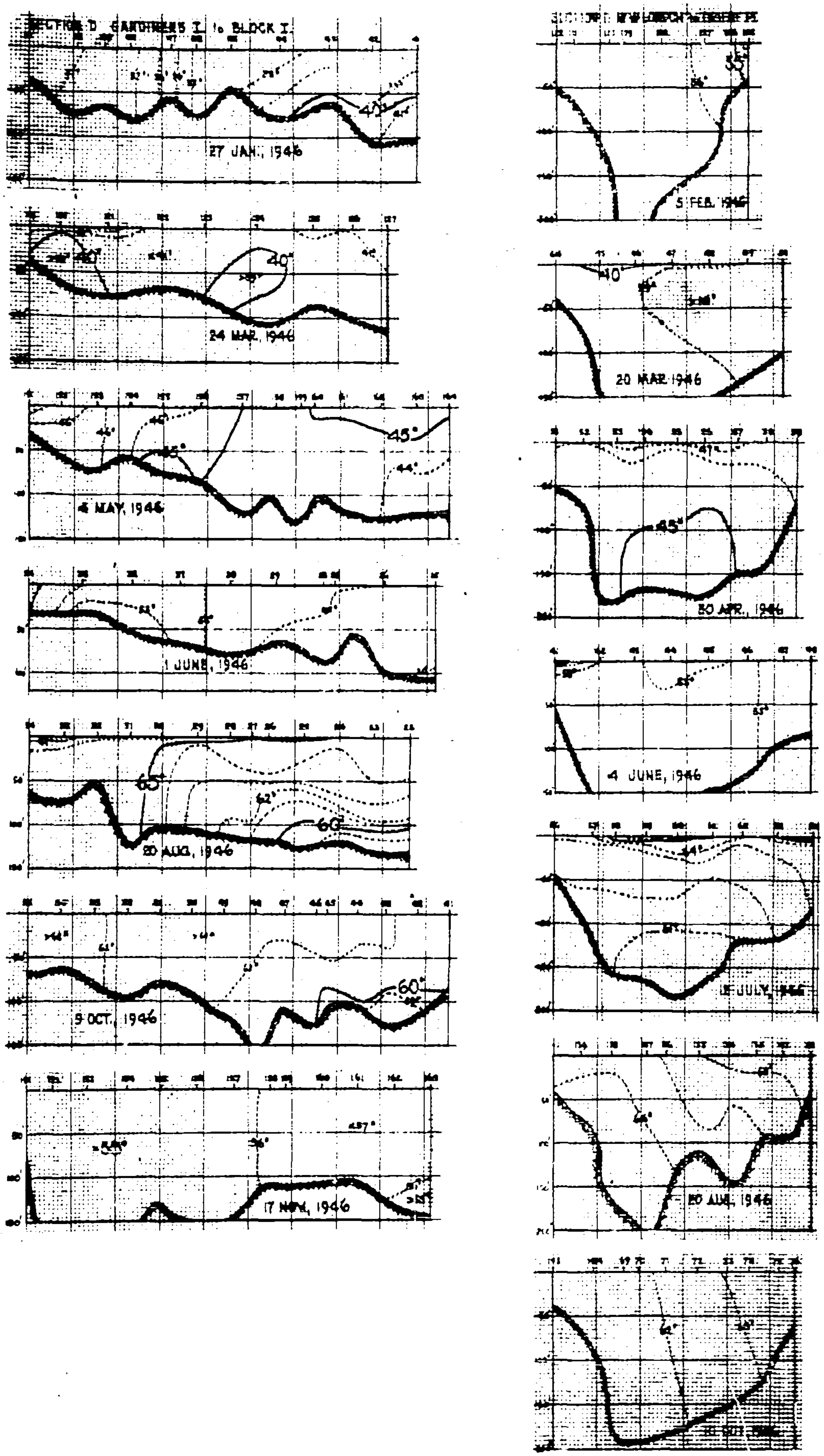

27 JAN., 1946
24 MAR. 1946
40°
4 MAY, 1946
45°
1 JUNE, 1946
20 AUG., 1946
65°
60°
9 OCT., 1946
60°
17 NOV., 1946
35°
5 FEB. 1946
40°
20 MAR. 1946
45°
30 APR., 1946
4 JUNE, 1946
20 AUG. 1946

FIGURE 22

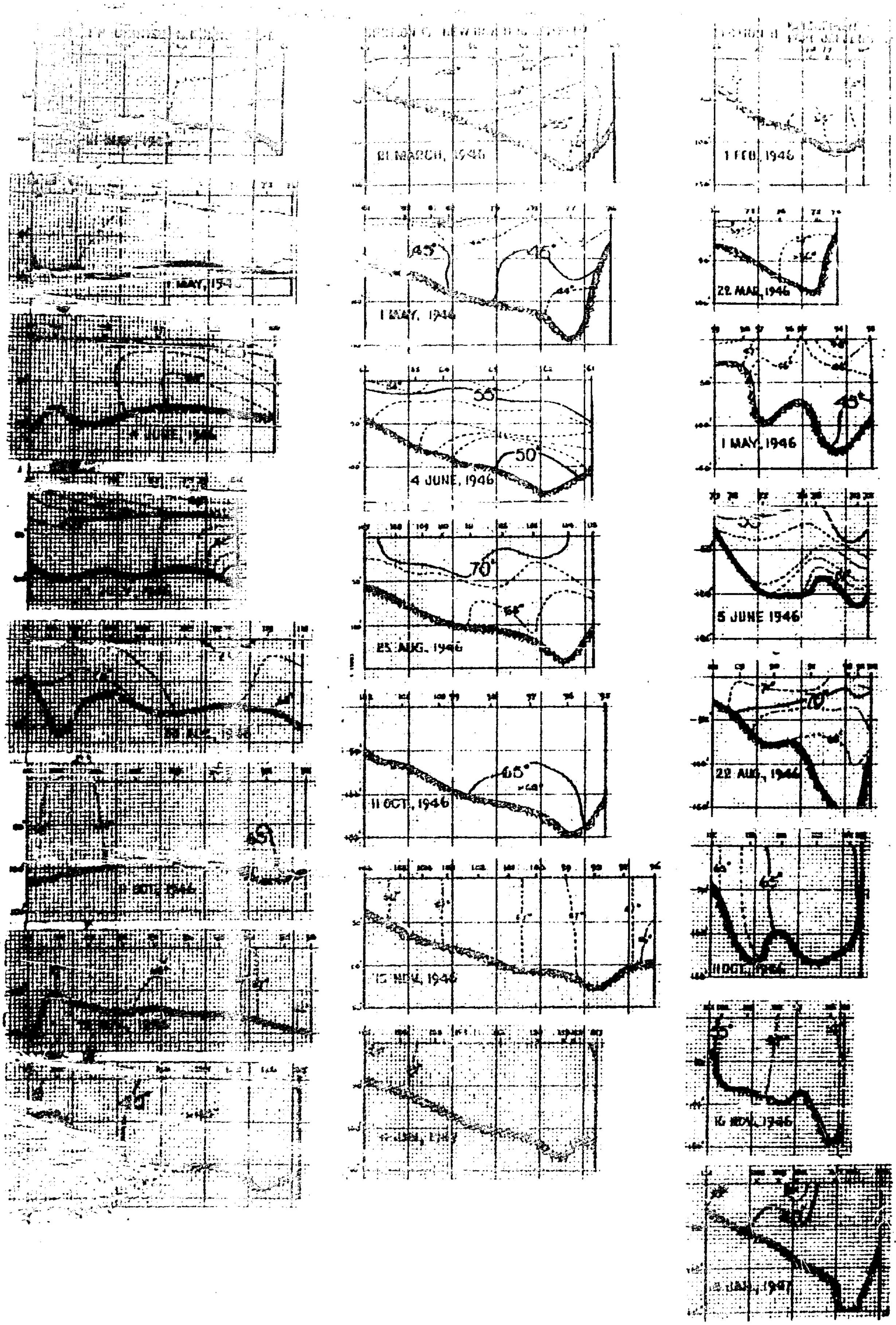

21 MARCH, 1946
1 FEB, 1946
45°
46°
1 MAY, 1946
22 MAR, 1946
55°
50°
4 JUNE, 1946
1 MAY, 1946
70°
25 AUG., 1946
5 JUNE 1946
65°
11 OCT., 1946
70°
22 AUG., 1946
15 NOV., 1946
16 NOV., 1946

FIGURE 23

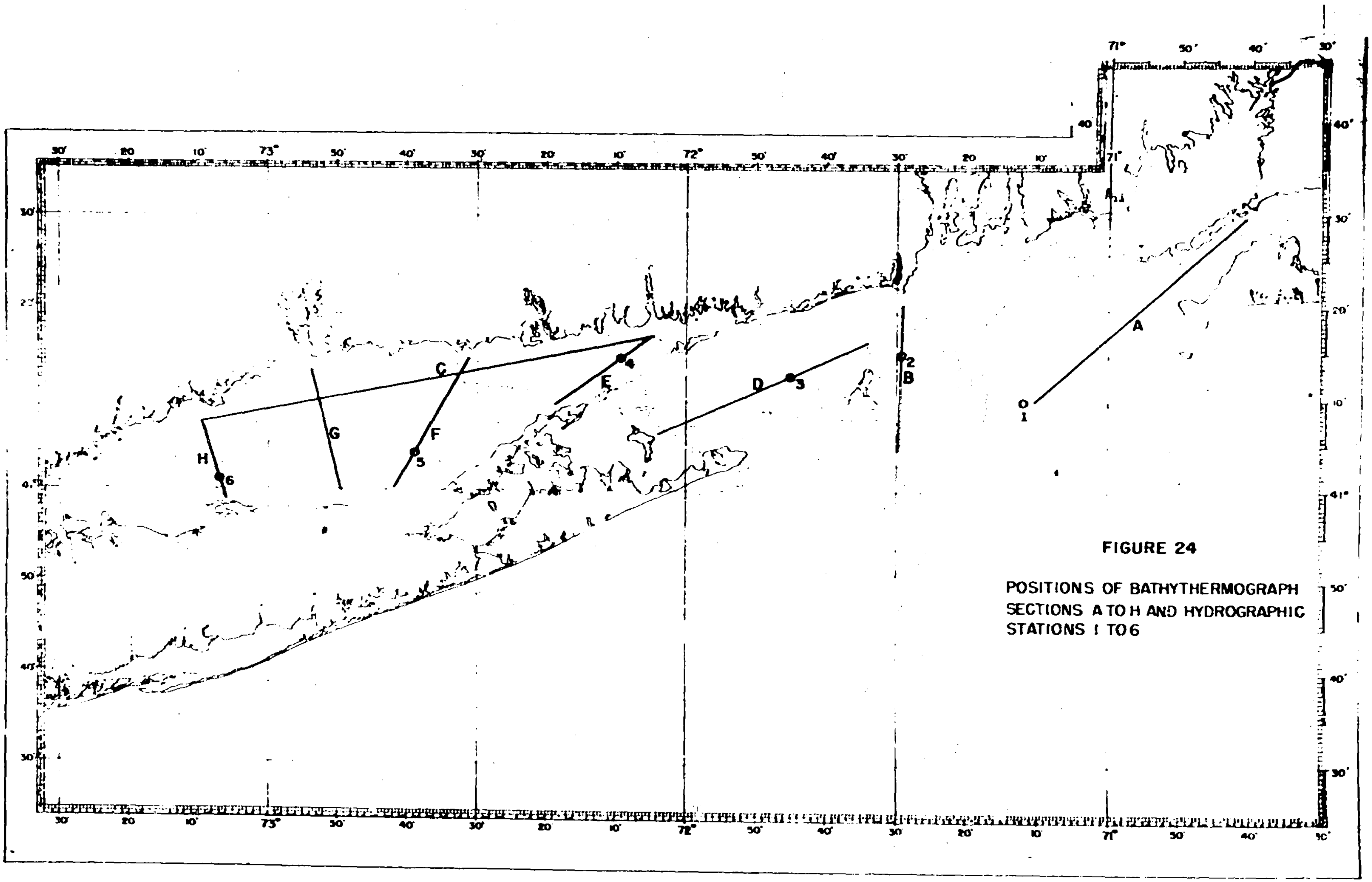


FIGURE 24

POSITIONS OF BATHYTHERMOGRAPH SECTIONS A TO H AND HYDROGRAPHIC STATIONS 1 TO 6 data is not sufficient to determine the density distribution in detail, but Figure 25 shows the observed increase of density with depth at various stations, the approximate positions of which are included in Figure 24. Each set of points is derived from the observations at a single station. While the data are arranged to show in a general way the seasonal trends in density structure, it appears likely that much of the irregularity in the curves results from local variability rather than true seasonal changes.

QUANTITATIVE ANALYSIS OF DISTRIBUTION

The Long Island and Block Island Sounds are similar in their main features of temperature and salinity distribution to many other semi-enclosed coastal waters in temperate regions. Thus the representation that has been made of the interaction between this distribution and oceanographic processes is largely a conventional picture that has been presented before in discussions of other localities. However, there is much to be gained from going a step further and developing a quantitative analysis of distribution, since it will check the validity of the qualitative explanation, add details about the relative importance of particular oceanographic processes, and obtain general oceanographic information that may be useful in the study of other regions.

Long Island Sound appears to be an area that can be studied readily by quantitative methods. Its tidal currents and freshwater drainage can be computed with considerable accuracy. Moreover, since it is a narrow body of water in

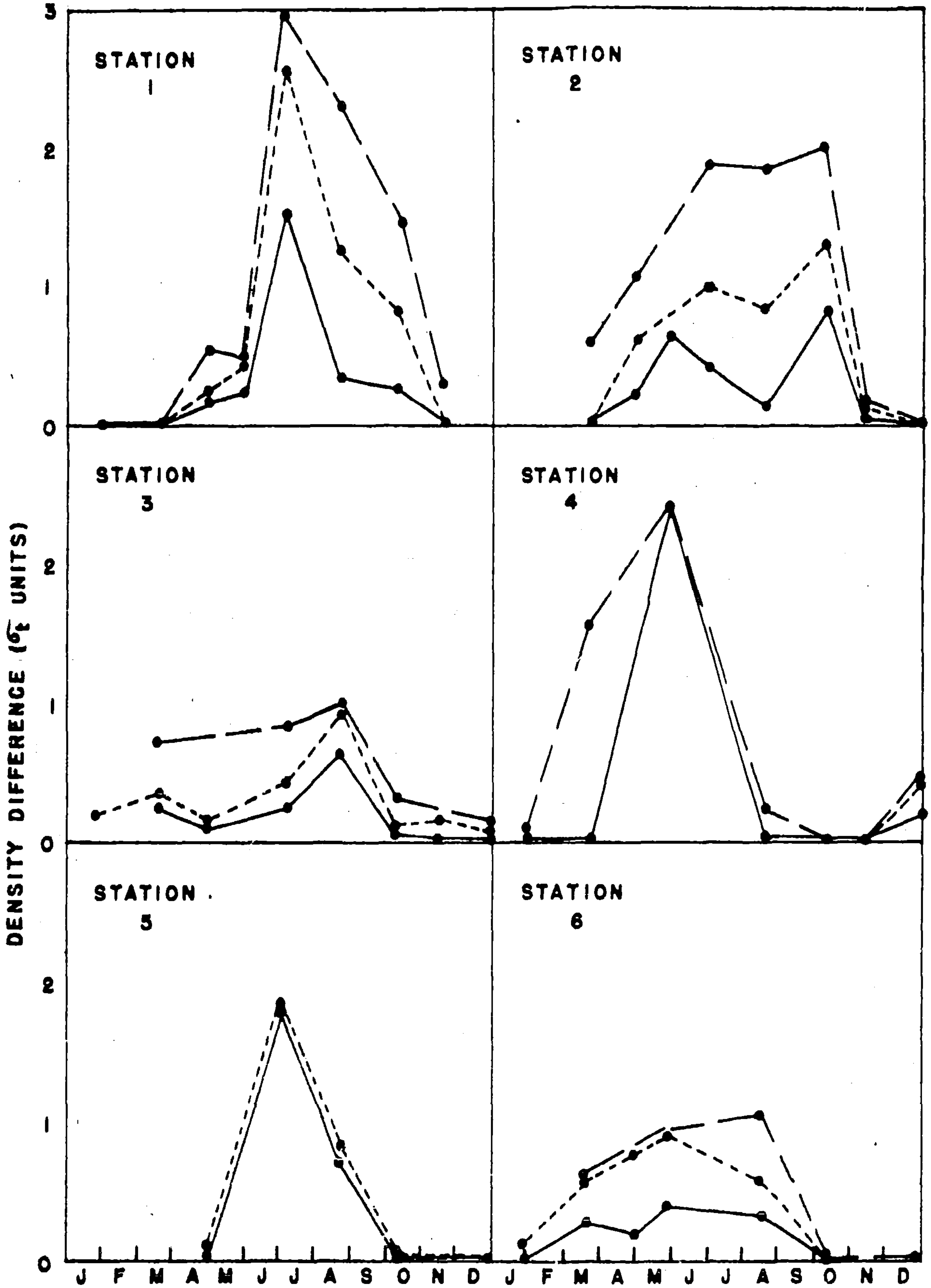


FIGURE 25. INCREASE IN DENSITY BETWEEN 0 AND 30 FT. ——; 0 AND 65 FT. - - - -; 0 AND 100 FT. — —.

which the major gradients in temperature and salinity are parallel to the long axis of the Sound, there will be no great error in reducing the mathematical treatment of horizontal mixing and transport to a consideration of transfer along this one axis. Block Island Sound presents more difficult problems, and the material at hand is not adequate for quantitative analysis.

Bathymetry of Long Island Sound

The study requires estimates of the area and volume of the Sound and of certain subdivisions of it. The necessary data were computed from planimetric tracings of the U. S. C. and G. S. charts, and the results are shown in Table I.

Freshwater drainage

Data largely obtained from Suttie (5) show that three rivers supply the major inflow into Long Island Sound. The Connecticut River ranks first with a drainage basin of 11,200 sq. mi. (statute); the Housatonic River drains 1930 sq. mi. and the Thames River 1400 sq. mi. Smaller rivers and streams of Connecticut, Long Island and the mainland of New York State contribute drainage from 1290 sq. mi. Thus the total drainage basin of Long Island Sound is 15,920 sq. mi.

Data on river discharge were obtained from the series of Water Supply Papers published by the U. S. Geological Survey. Figure 26 summarizes their information on the seasonal variation in the discharge from three rivers of the Long Island Sound

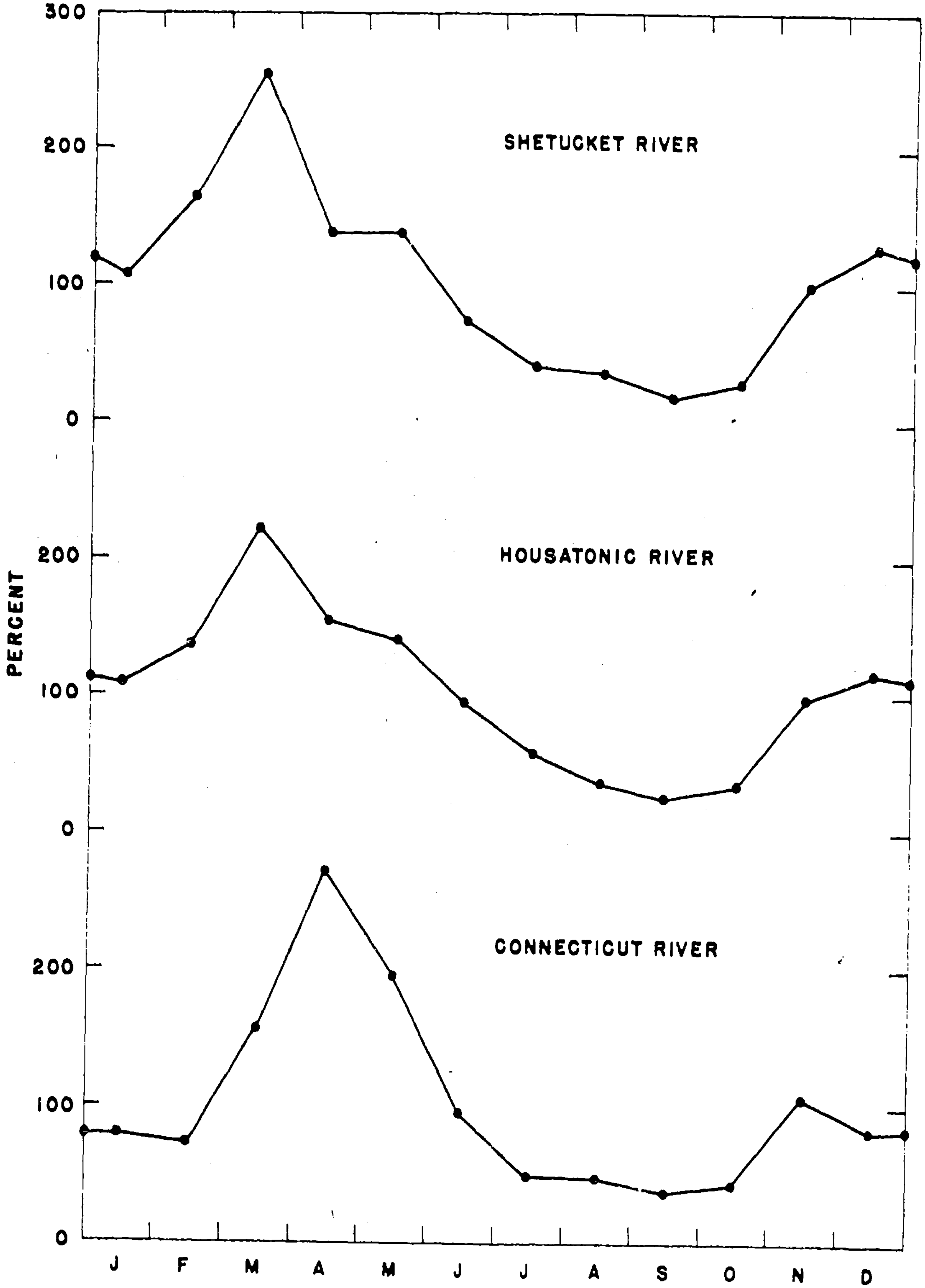


FIGURE 26. SEASONAL PERCENTAGE VARIATION IN RIVER DISCHARGE. ANNUAL MEAN=100%

TABLE I

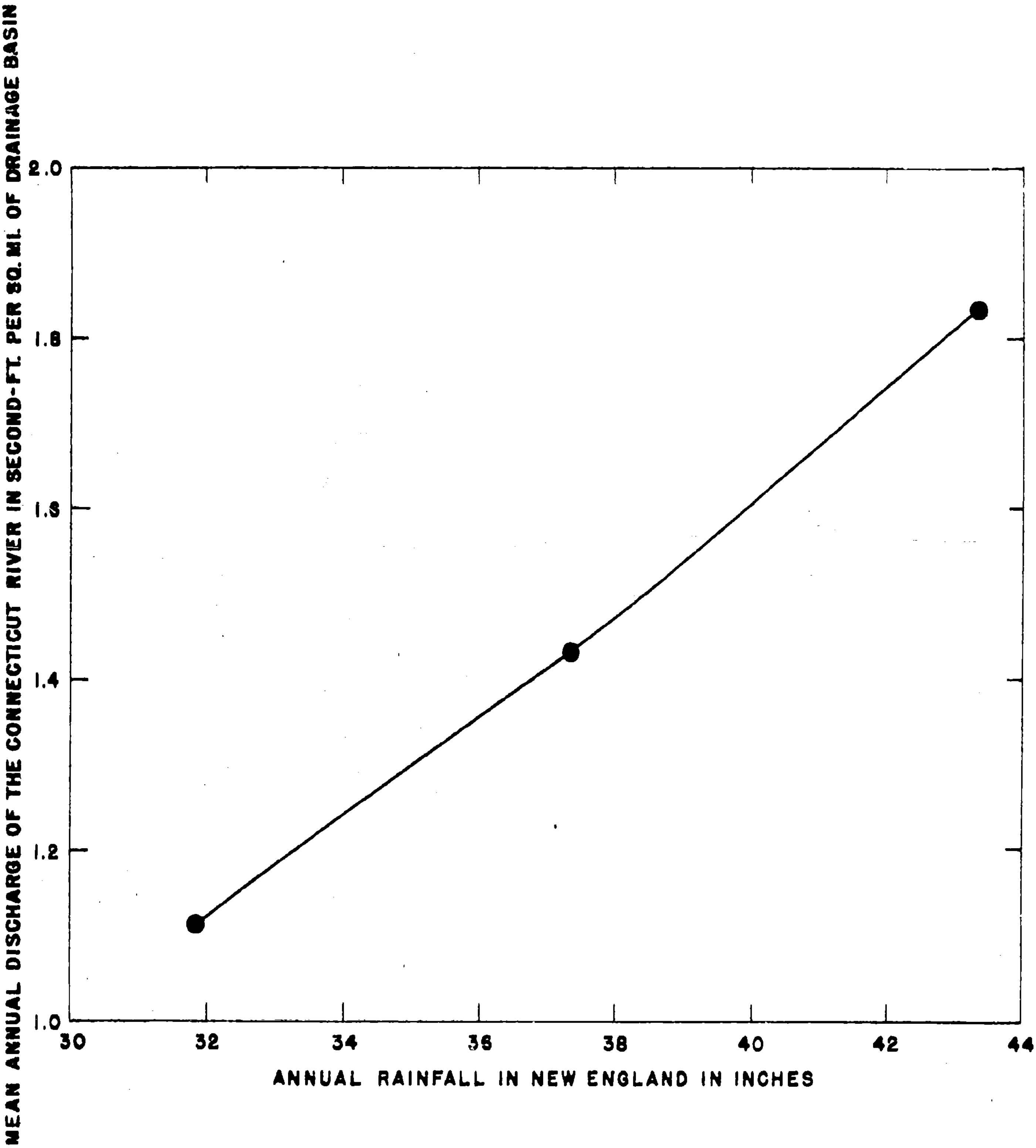
Area and Volume of Long Island Sound

The Sound was subdivided by drawing north-south lines across the U. S. C. and G. S. charts of the Sound at intervals of 10' of longitude. The areas at mean low and at successive depth intervals were measured planimetrically. The following figures are based on these measurements, which include Fishers Island Sound but not the waters south and east of Fishers Island, Gull Islands, etc.

	Area M.W.L. Naut. sq.mi.	Volume in cu.ft. x 10^8 between successive depth contours 0-20	20-30	30-45	45-60	60-75	75-100	100-125	125-150	150-175	175+	Total Vol.
71°50'W to 72°00'W	15.8	87	22	12								121
72°00' to 72°10'	38.0	270	121	146	117	98	135	123	107	83	165	1365
72°10' to 72°20'	59.0	411	184	253	238	222	315	219	114	33		1989
72°20' to 72°30'	80.5	560	251	340	290	234	255	138	73	17		2158
72°30' to 72°40'	116.7	827	384	522	465	360	256	20	2			2836
72°40' to 72°50'	128.8	908	419	563	500	453	416	64	4			3327
72°50' to 73°00'	130.0	904	404	534	439	347	358	129	27			3142
73°00' to 73°10'	99.6	688	300	380	309	238	260	132	40			2347
73°10' to 73°20'	98.0	685	307	410	323	201	172	55	1			2154
73°20' to 73°30'	70.7	448	174	210	158	113	99	31	6			1239
73°30' to 73°40'	54.2	343	135	163	90	34	20	3				788
73°40' to 73°50'	37.4	210	65	65	42							382
Total	928.7	6341	2766	3598	2971	2300	2286	914	374	133	165	21848

drainage basin, plotted as the percentage deviation from the mean annual discharge during the period from October 1940 to September 1943. The curves in part reflect seasonal variations in rainfall but are considerably modified by the effects of evaporation, which is most pronounced in the summer and early autumn, and of melting snow in the spring. The latter effect is especially pronounced and occurs slightly later in the season in the Connecticut River, which contains as a considerable part of its drainage basin upland areas of northern New England where the snow cover is heavier and lasts longer than along the Connecticut and New York shore.

During the three years examined, there was a simple relation between the mean annual river discharge and the annual rainfall of New England, as shown in Figure 27. This curve can be used to estimate river discharge for the year 1946, which is of particular interest from the standpoint of the present oceanographic survey, and for which the observations on river discharge have not yet been published. In 1946 the mean rainfall in New England was 38.41 inches (Monthly Weather Review). Applying this value to Figure 27, it is estimated that the mean river discharge was 1.5 second-feet per sq. mi. of drainage basin. In estimating the total discharge into Long Island Sound, the figure of 1.5 second-feet is applied directly to the curves in Figure 26 for seasonal variations in the flow of the Connecticut and Housatonic Rivers. It is then assumed that the variations



MEAN ANNUAL DISCHARGE OF THE CONNECTICUT RIVER IN SECOND-FT. PER SQ. MI. OF DRAINAGE BASIN
2.0
1.8
1.6
1.4
1.2
1.0
30
32
34
36
38
40
42
44
ANNUAL RAINFALL IN NEW ENGLAND IN INCHES

FIGURE 27

in the Thames R. are the same as the Housatonic R. and that the other rivers of New York and Connecticut are the same as the Shetucket, a small river with a drainage basin of 400 sq. mi.

To obtain the total freshwater increment in Long Island Sound, the rainfall on the surface of the Sound must be added to the calculated river drainage (the effect of evaporation from the surface of the Sound is neglected, producing an error of a few percent in the final result). Figure 28 shows the seasonal curves for drainage and the combined estimate. The total volume of fresh water entering the Sound during the year was estimated to be 853 x 10^9 cu. ft., or 39% of the volume of the Sound (34% drainage, 5% rainfall on the surface).

Tides and currents

The tides in the area are essentially standing waves, and in the central reach of Long Island Sound, the time of slack water coincides with high and low tides. However, at the eastern end, ebb follows high tide by one and a half to two and a half hours.

Figure 29 shows the time of the tide related to the reference point of New London. The figures are from the U. S. C. and G. S. tide tables and are applicable to both high and low water. It is apparent that there is a progressive lag in the time of the tide from east to west

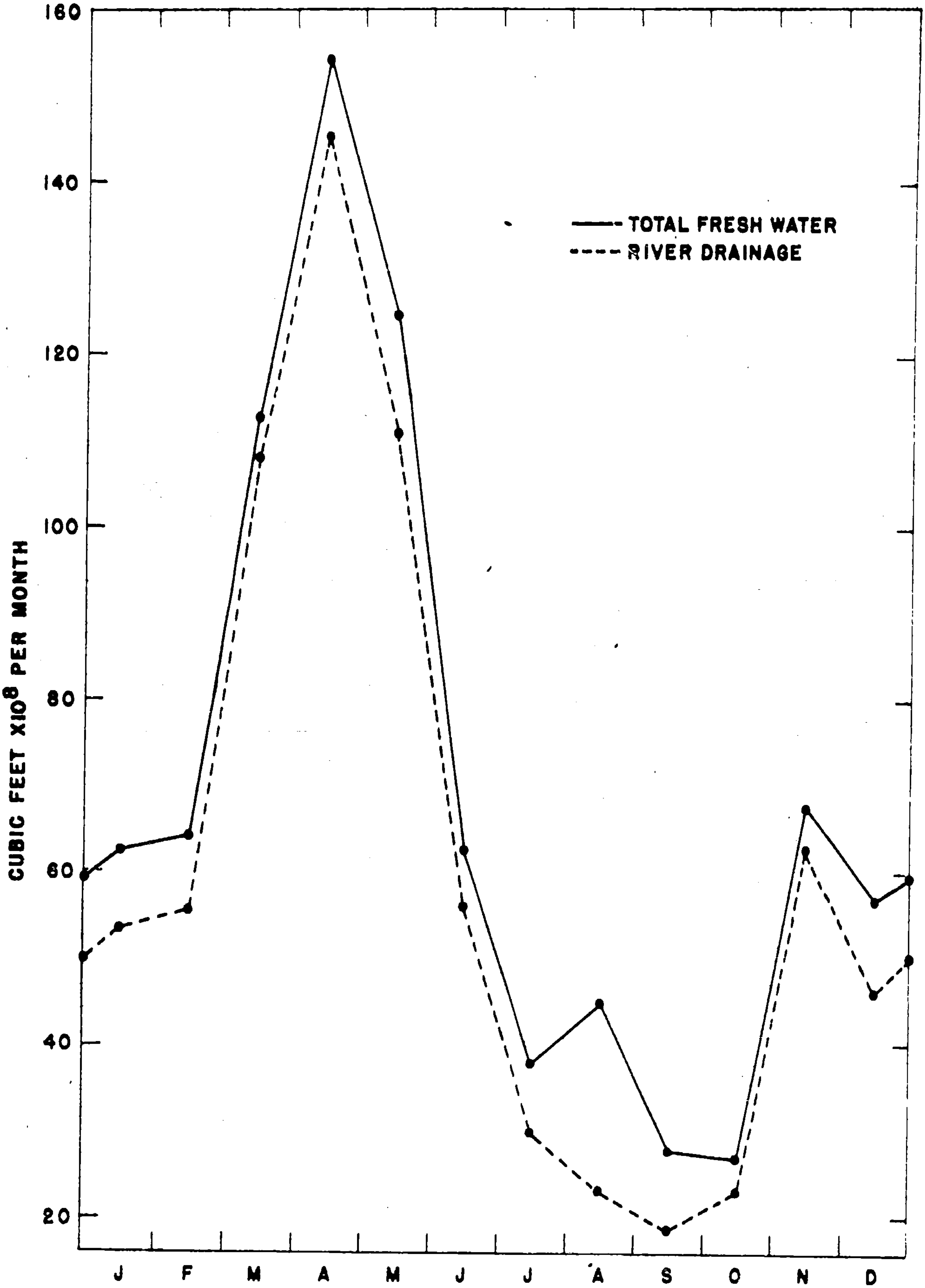


FIGURE 28. SEASONAL VARIATION IN FRESH WATER INCREMENT IN LONG ISLAND SOUND.

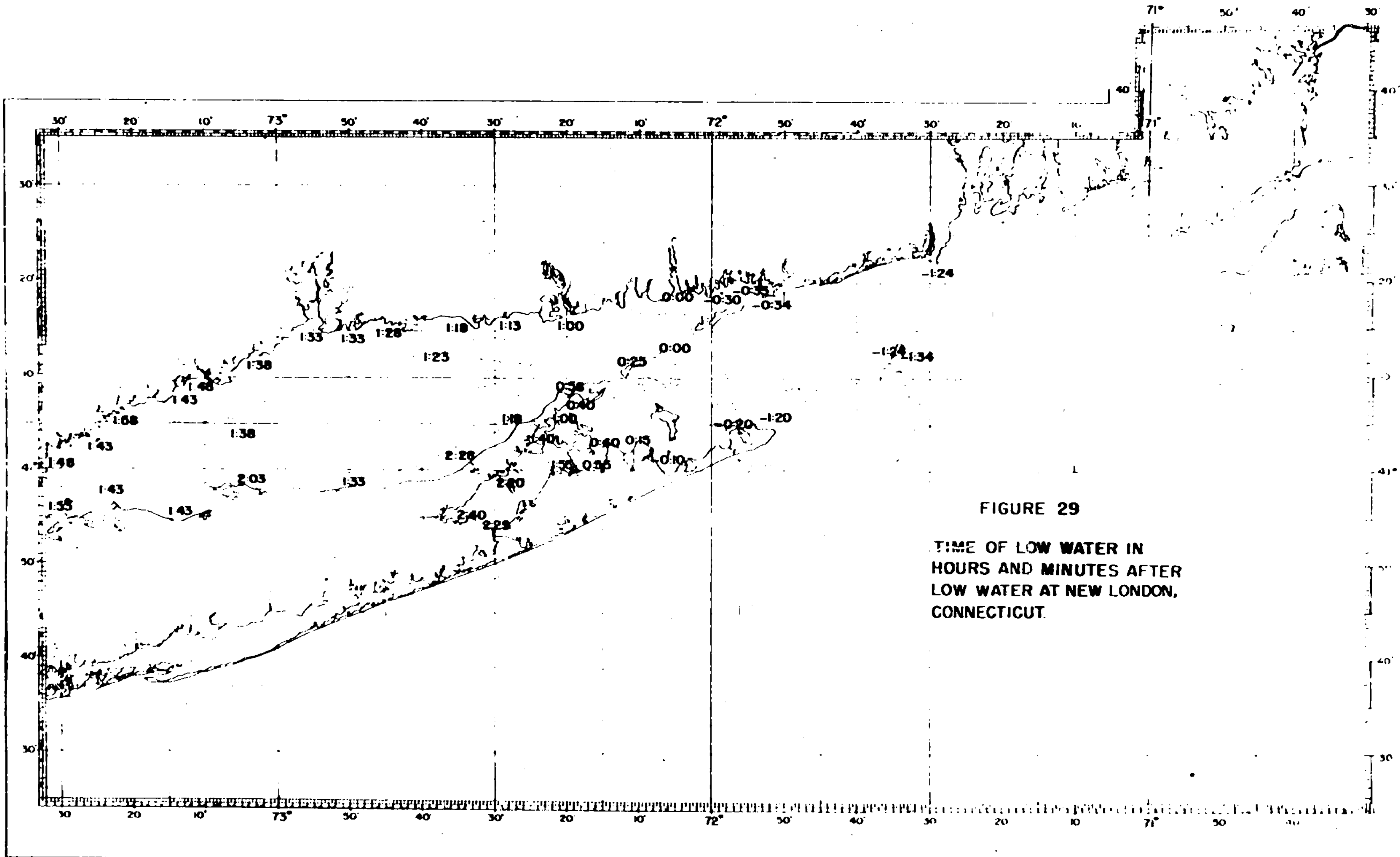


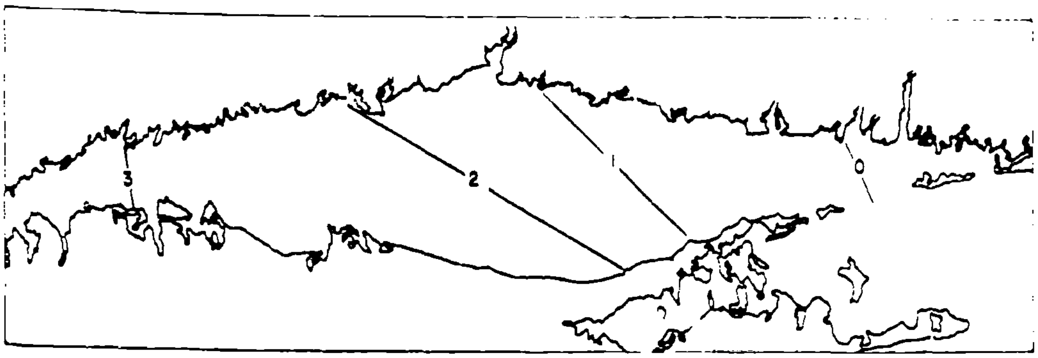
FIGURE 29

TIME OF LOW WATER IN HOURS AND MINUTES AFTER LOW WATER AT NEW LONDON, CONNECTICUT except for certain irregularities along the north shore of Long Island. From the same tables it is found that the mean range of the tide is about 2.5 ft. along the shore of Block Island Sound and the eastern part of Long Island Sound and increases in a westerly direction to a maximum of 7.3 ft. The spring range of the tide is 3.1 to 8.6 ft.

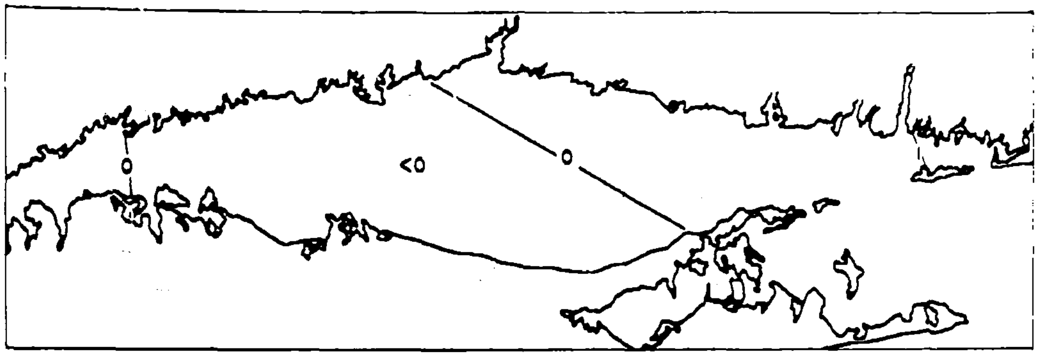
The data on the height of the tide provide a means of estimating the magnitude of the tidal transport in Long Island Sound and the average current velocity along the east-west axis. A twenty-four hour period was chosen from the tide tables when the predicted tides approximated the mean range (1500 25 February to 1500 26 February, 1945). The tidal height was computed for hourly intervals during this period. Samples of the result are shown in Figure 30.

The change in the volume of water in any particular area or a specified fraction of it is readily determined as the product of the area and the change in the height of the tide. By summing the change in volume for successive small areas, the total inflow and outflow of the Sound during a tidal cycle was found to be of the order of 8.2% of the volume of water below mean low water.

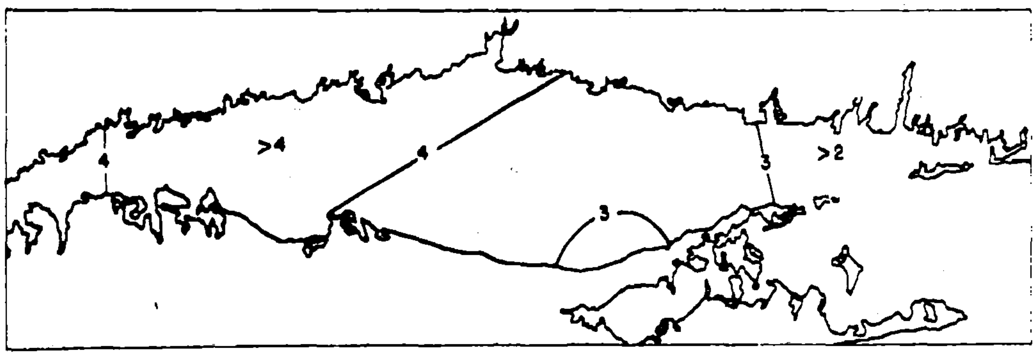
Adopting the simplifying assumption that the only significant tidal interchange occurs at the eastern end of the Sound, an approximately correct estimate of the mean current velocity in the east-west direction is readily obtained. The volume transport across any given cross-section of the Sound is equal to the change in the total volume of



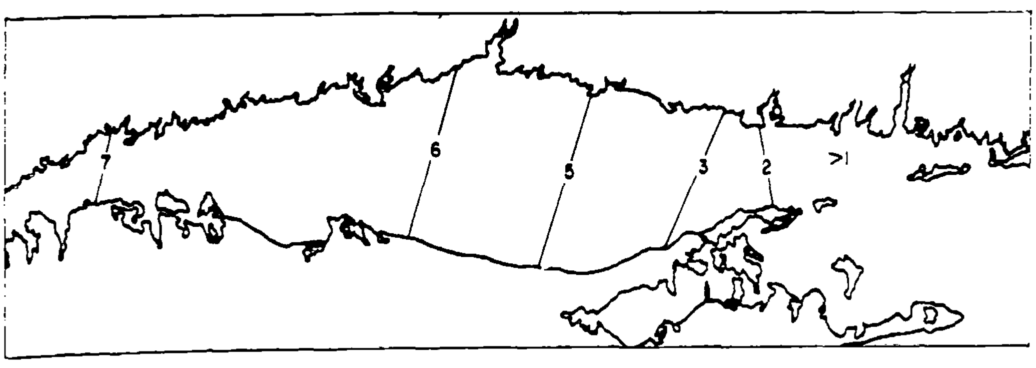
LOW TIDE AT NEW LONDON



MID - FLOOD



HIGH TIDE



MID - EBB

FIGURE 30. HEIGHT IN FEET ABOVE MEAN LOW WATER AT 0, 3, 6, AND 9 HOURS AFTER LOW TIDE AT THE REFERENCE POINT OF NEW LONDON.

water westward of the section. Knowing the cross-sectional area, the volume transport can be transformed into a computed average current velocity. Figure 31 shows these calculated velocities through five cross-sections of the Sound. Also shown is the mean velocity of the interchange between the Long Island and Block Island Sounds through the various passes between Watch Hill Point, Rhode Island, and Orient Point, Long Island. As might be expected, the maximum velocity occurs in the passes, and the current is also relatively strong in the constricted eastern portion of Long Island Sound. The figure illustrates the gradual decrease in velocity toward the west and the progressive lag in the stage of the tide such that the ebb in the western end begins about two hours later than in the passes.

This gross picture of tidal currents ignores many local variations. Surface currents in the area have been charted by the Coast and Geodetic Survey. Variations in relative strength are on the whole similar to what has just been described, but the magnitude of the surface currents is between 100% and 150% of the computed mean velocity for the whole cross-section. This is in accord with the observations obtained elsewhere of the relation between maximum and mean flow in channels (8, page 568). Second, considerable variability exists in both the speed and the time of reversal in the different passes at the eastern end of the Sound. Third, there appears to be a tendency toward the establishment of a

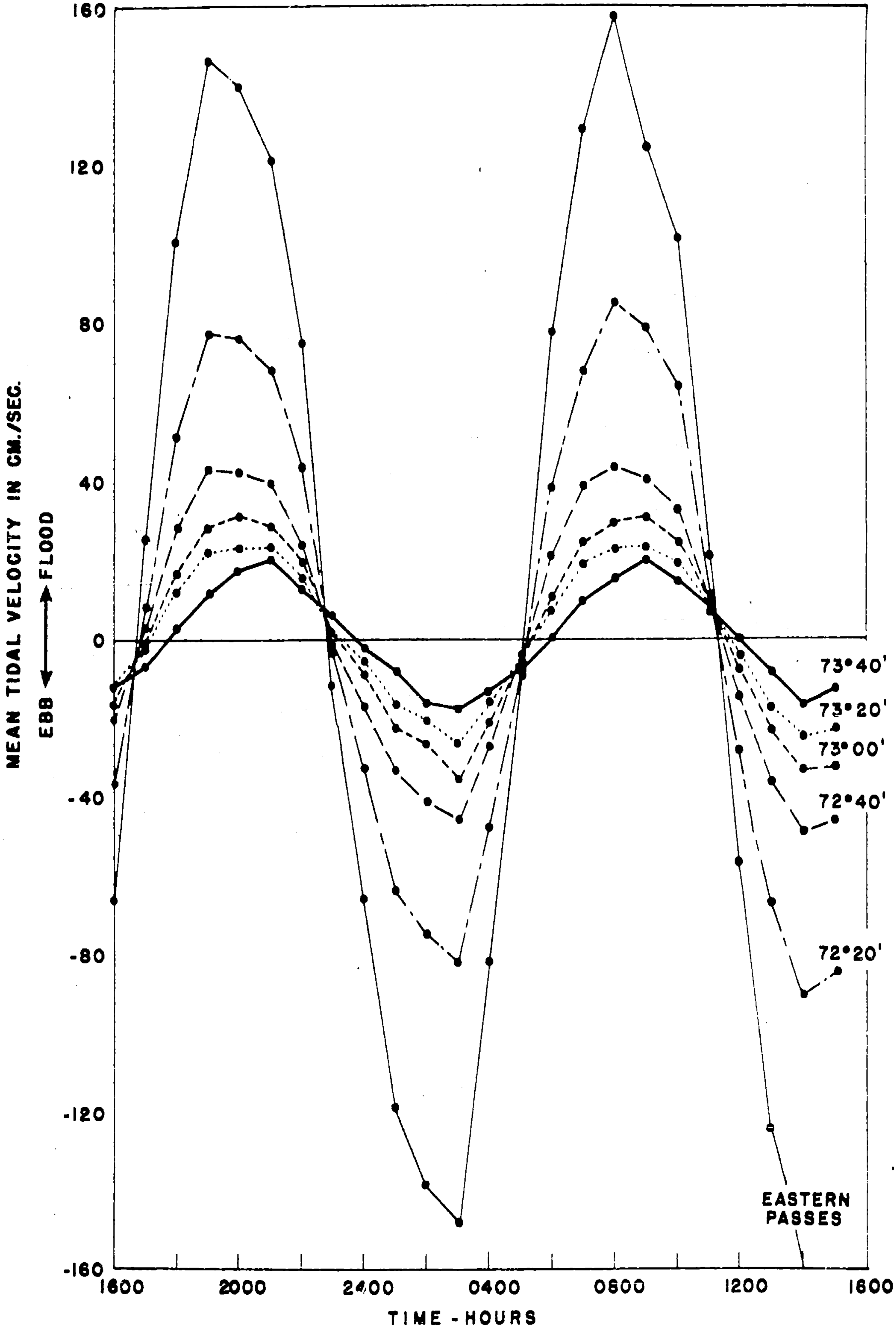

MEAN TIDAL VELOCITY IN CM./SEC.
EBB
FLOOD
160
120
80
40
0
-40
-80
-120
-160
1600
2000
2400
0400
0800
1200
1600
TIME - HOURS
73°40'
73°20'
73°00'
72°40'
72°20'
EASTERN PASSES

FIGURE 31

semi-rotary tidal movement in the central area of the Sound, and this of course does not appear in the computation of east-west velocities.

Prytheroh (3) examined the tidal currents in the northern part of the Sound near Milford, Connecticut. He found that the ebb tide travelled approximately ESE with a maximum speed of 0.6 kt. The flood had an initial direction of WNW and rotated 140° clockwise between low and high water. According to Prytheroh, this tendency of the current to swing to the east after mid-flood results in a resultant movement of two miles ENE during a complete tidal cycle. He furthermore concluded from drift bottle experiments that this movement was part of a large scale clockwise eddy in the central part of the Sound superimposed on the basic east-west drift and resulting in a net transport eastward along the Connecticut shore and westward along most of the north shore of Long Island. However, in the latter area there was some evidence of a small counter-clockwise eddy (the more usual type of tidal movement) between Hortons and Herods Point. The magnitude of the rotational movement cannot be estimated readily from the drift bottle experiments. The fastest recorded drifts were about 0.2 kt. averaged over periods of nine to fifteen days, but it seems likely that this is a maximum figure for the net transport.

It has been pointed out previously that tidal oscillations travelling parallel to the long axis of the Sound would tend, by the turbulent mixing that they generate, to produce a salinity gradient such that the isohalines would cross at right angles to the axis. Any tendency toward rotary tides would distort the isohalines. It will be noted in re-examination of the figures on salinity distribution that there are several cases in which the isohalines are slightly rotated, extending further to the east on the northern side of the Sound. This is probably the result of the eddy described by Prytherch, although the situation is further complicated by the uneven distribution of river outlets. However, it is apparent by inspection that the effect of the eddy on salinity and temperature distribution is not important enough to mask the effect of the main east-west oscillation, nor will there be any large error in the quantitative analysis if the eddy is ignored.

The continual increment in the volume of Sound water resulting from river drainage must be balanced by a corresponding net transport to the east and eventual outflow from the Sound. The magnitude of this transport is so small compared with tidal interchange that it probably could not be detected by actual observation, but it can be computed from data previously presented on drainage and is found to vary from about 0.004 kt. in the central part of the Sound to 0.06 kt. in the eastern passes.

The details of the interchange of water masses cannot be made fully clear by calculations of net transport. The temperature and salinity distributions suggest that the transport to the east is greater near the surface than it is in the bottom water. The latter may have a westward transport. In this case the computed net transport simply would represent the difference between the transports in the two layers. Failure to describe this situation accurately will lead to some error in the quantitative analysis, particularly the study of temperature distribution in the eastern part of Long Island Sound.

Diffusion processes

Table II shows the mean salinity, surface to bottom, calculated on a volumetric basis, which will be used to determine the magnitude of lateral diffusion in the central body of Long Island Sound water between Longitudes 72°20' and 73°00'W. A glance at the table shows that the salinity increases from west to east and that in any one area there is a considerable change from one cruise to the next. The processes concerned will first be examined individually.

1. According to previous calculations, there is a net transport eastward. Since the salinity increases to the east, into any particular area there is a constant transfer of water of lower salinity. The magnitude of this effect in a second's time is expressed by $-v \cdot \partial S/\partial x$, in which v is transport velocity in cm. per second, and $\partial S/\partial x$ is the increase in salinity (defined for present purposes as grams of salt per gram of water) per cm. of horizontal distance eastward.

2. There is a continual lateral exchange of water by turbulence, which is quantitatively expressed by the magnitude of A_x, the coefficient of horizontal eddy diffusion. If a horizontal salinity gradient exists, turbulence will result

TABLE II

Mean Salinity ($^{o}/oo$) of Long Island Sound

Average salinity depth curves were drawn for each area. The volume of water in successive depth ranges was multiplied by the mean salinity value of each range, and the sum of the products was divided by the total volume of water. Cruises 301 and 311 omitted because of incomplete data.

Cruise No.	303	306	308	434	436	438	440
72°10' to 72°20'	28.12	28.97	28.35	29.76	29.60	30.80	30.28
72°20' to 72°30'	26.99	27.14	27.44	28.31	29.56	30.40	29.80
72°30' to 72°40'	26.80	27.74	26.52	27.61	28.46	28.80	28.94
72°40' to 72°50'	26.66	27.01	26.72	27.52	27.86	28.50	28.47
72°50' to 73°00'	26.40	27.08	26.75	27.04	27.72	28.20	28.38
73°00' to 73°10'	26.31	26.52	26.06	27.13	27.50	28.20	28.20
72°20' to 73°00'	26.69	27.23	26.81	27.56	28.29	28.83	28.82

in a net transfer of salt which is expressed by $A_x \partial S/\partial x$. If the gradient is uniform, salt will be transferred out of a unit volume of water as rapidly as it goes into it (assuming A_x to be constant). But if the gradient increases or decreases, there will be a change in the salt content, amounting in unit time to $A_x . \partial^2 S/\partial x^2$.

3. There is a continual tendency to freshen the Sound water by river drainage and rainfall, the average effect of which is determined by the ratio of the freshwater increment in unit time to the volume of Sound water diluted. Then the absolute change in salt content in a second's time is the product of this ratio and the mean salinity of the water. It is denoted by the symbol $\partial S_f/\partial t$.

The net effect of these three processes determines the change in salinity that will occur in an average water mass in the central portion of the Sound in a second's time. The equation for this change, $\partial S/\partial t$ is

$$\frac{\partial S}{\partial t} = \frac{\partial S_f}{\partial t} + A_x \frac{\partial^2 S}{\partial X^2} - V \frac{\partial S}{\partial X}$$

Table III shows the mean values for the terms of the equation calculated for the periods between successive cruises. Details of the methods of calculation are appended. The only unknown term in the equation is the coefficient of diffusivity A_x, which therefore can be calculated readily and is shown in the last line of the table. These calculated coefficients fall within the general limits of previously computed

TABLE III

The Calculation of Horizontal Diffusion

Cruises	303-306	306-308	308-434	434-436	436-438	438-440
Time between cruises (seconds)	$3.6x10^6$	$2.8x10^6$	$7.1x10^6$	$4.2x10^6$	$3.0x10^6$	$4.2x10^6$
Change in salinity (72°20' to 73°00'W)	0.54	-0.42	0.75	0.73	0.54	-0.01
*$\partial S/\partial t$	$15.0x10^{-11}$	$-15.0x10^{-11}$	$10.5x10^{-11}$	$17.4x10^{-11}$	$18.0x10^{-11}$	$-0.2x10^{-11}$
Mean $\partial S/\partial x$						
72°20' to 73°00'W	$7.8x10^{-11}$	$9.0x10^{-11}$	$23.4x10^{-11}$	$37.0x10^{-11}$	$48.1x10^{-11}$	$43.1x10^{-11}$
72°10' to 72°40'W	$45.8x10^{-11}$	$54.8x10^{-11}$	$71.3x10^{-11}$	$59.0x10^{-11}$	$58.3x10^{-11}$	$59.5x10^{-11}$
72°40' to 73°10'W	$15.0x10^{-11}$	$20.5x10^{-11}$	$18.8x10^{-11}$	$13.5x10^{-11}$	$11.8x10^{-11}$	$10.0x10^{-11}$
*Mean $\partial^2 S/\partial x^2$	$7.3x10^{-17}$	$8.3x10^{-17}$	$12.5x10^{-17}$	$10.9x10^{-17}$	$10.7x10^{-17}$	$11.8x10^{-17}$
Mean transport velocity, V (cm./sec.)	.038	.034	.021	.014	.014	.029
*$V. \partial S/\partial x$	$.29x10^{-11}$	$.30x10^{-11}$	$.49x10^{-11}$	$.52x10^{-11}$	$.68x10^{-11}$	$1.25x10^{-11}$
Fresh water drainage (%)	6.57	5.44	2.18	1.37	2.00	2.91
∂S_f	-1.77	-1.47	-.53	-.38	-.57	-.84
* $\partial S_f/\partial t$	$-49.1x10^{-11}$	$-52.4x10^{-11}$	$-8.3x10^{-11}$	$-9.0x10^{-11}$	$-19.0x10^{-11}$	$-20.0x10^{-11}$
A_x	$8.8x10^6$	$4.5x10^6$	$1.5x10^6$	$2.5x10^6$	$3.5x10^6$	$1.8x10^6$

From the time between the midpoints of successive cruises and the change in salinity (from Table II), the rate of change $\partial S/\partial t$ is calculated. The horizontal salinity gradient $\partial S/\partial x$ in the central part of the Sound is computed as the difference between the mean salinity of the eastern group of data (72°20'to72°30'W) in Table II and the western group (72°50'to73°00'W) divided by the distance between the midpoints of the groups (72°25'to 72°55'W). The figures presented are the means of the two cruises represented in each column of the table. Similarly the mean gradients in the eastern and western halves of the area were determined separately, as shown in the next two lines of the table. The difference between these gradients, again divided by the distance between their mid-points, is the rate of change of the gradient $\partial^2 S/\partial x^2$. The next two lines are the computed

TABLE III (continued)

net transport velocity in cm/sec. and the product of this figure and the horizontal salinity gradient (72°20' to 73°00'W). Next the estimated drainage between cruises is listed as a percentage of the volume of Sound water, multiplied by the mean salinity to give the increase in salinity resulting from drainage (ΔS_f), and this divided by the time is the rate of change due to dilution ($\partial S_f/\partial t$). The quantities marked with asterisks are all the variables in the equation of distribution except A_x, which is then calculated and is shown in the last line of the table.

values for oceanic waters, which Sverdrup, Johnson and Fleming (6) list as 10^6 to 10^8 g/cm/sec. That they lie near the lower limit of this range is to be expected in a relatively small body of water. The apparent seasonal variation, with the smallest values of $\underline{A_x}$ in summer and the largest in midautumn, may or may not be valid. Precise conclusions should not be drawn from such a small set of data. It is apparent, however, simply from the fact that the computed coefficients are of the right order of magnitude throughout, that the observed salinity distribution is in accord with oceanographic theory of the interplay between diffusion, transport and drainage.

Vertical transfer of heat and salt are effected by turbulence in a manner analogous to the lateral diffusion that has just been discussed. Temperature rather than salinity will be used for the analysis because of the accurate estimates of vertical gradients that can be obtained from bathythermograms and the superior quantity of temperature records available.

For purposes of analysis the part of Long Island Sound between 72°00'W and 73°10'W is divided into seven areas, each comprising 10' of longitude and extending in a north-south direction across the width of the Sound. In each case the mean rate of diffusion will be determined at depths of 30 ft., 60 ft. and 100 ft. or as many of these as the depth of water permits.

Seasonal gains and losses of heat in the surface layer result in the development of vertical temperature gradients, which, however, tend to be equalized by the turbulent transfer of water. The amount of heat passing through a horizontal surface of 1 cm^2 in a second of time is the product of the coefficient of vertical eddy conductivity $\underline{A_z}$ and the change in temperature per cm. of depth $\underline{\partial \mathfrak{v} / \partial z}$.

This transfer results in an accumulation or dissipation of heat in the underlying water, so that the change in a unit of time in the heat content of the whole underlying water column may be used as an index of the rate of heat transfer. This relation is expressed by the equation

$$\frac{\partial \mathfrak{u}}{\partial t} = A_z \frac{\partial \mathfrak{u}}{\partial z}$$

in which $\underline{\partial \mathfrak{u} / \partial t}$ is the increase per second in calories in a column of water 1 cm^2 in cross section extending from the bottom up to the depth at which the rate of transfer is to be determined.

It is apparent that this equation is severely simplified. In the presence of horizontal temperature gradients in the lower water, lateral diffusion and transport will modify the rate of change of heat and may cause a serious error in the estimate of vertical turbulence. If the magnitude of these processes is known, the equation can be expanded to include them. Thus preliminary calculations were made containing correction factors based on the observed horizontal temperature gradients and the previous estimates of net transport and lateral diffusion. However, it was found that in no case did these effects account for as much as 1% of the temperature change. It does not seem worthwhile to include these minor corrections; therefore the data are developed according to the equation presented above. Tables IV and V show the observed mean temperature gradients and the mean rate of change in calories in the lower water between successive cruises. Application of these figures to the equation yields the coefficients of vertical conductivity shown in Table VI.

It will be noted that there are some question marks in Table VI. The figures are omitted because the calculations yield negative values for the conductivity coefficient, which are manifestly impossible and therefore indicate serious errors in the method. All such values were obtained in the eastern part of the Sound, where it is suspected that transport varies significantly with depth, thus invalidating the use of a mean transport value for the whole vertical column. In other words, this is a place where corrections should be made for horizontal distribution processes if the proper data were available.

The existence of a few patently invalid results may throw suspicion on the accuracy of the rest of the calculations. However, without denying the existence of a considerable amount of error, it is possible to show that the variation in the remainder of the data is in general accord with oceanographic theory. The coefficients are smaller in the spring and summer than in the autumn and winter, which is attributed to changes in the stability of the water column. They are

TABLE IV

Mean Temperature Decrease in Degrees x10^{-4} per cm. of Depth

Cruises	Depth range	72°00'-10'	72°10'-20'	72°20'-30'	72°30'-40'	72°40'-50'	72°50'-73°00'	73°00'-10'
303-306	0-60	3.33	4.72	5.97	6.71	6.21	9.65	11.38
	30-100	-0.14	0.86	0.38	--	--	4.71	4.43
	60-150	-1.43	0.57	--	--	--	--	--
306-308	0-60	3.90	4.53	5.26	3.81	6.13	10.11	9.16
	30-100	-0.22	1.29	1.10	--	--	6.12	6.87
	60-150	0.70	0.95	--	--	--	--	--
308-434	0-60	2.73	3.08	3.95	4.93	6.05	9.34	6.98
	30-100	-0.35	1.06	0.98	--	7.01	7.97	7.85
	60-150	0.85	1.01	2.03	--	--	--	--
436-438	0-60	0.25	0.25	-1.52	-0.93	-1.72	-1.80	-0.46
	30-100	-0.78	0.05	-1.42	-0.79	-1.68	-2.25	-1.43
	60-150	-0.96	0.17	-1.08	--	--	--	--
438-440	0-60	-0.11	-0.57	-1.01	-1.85	-3.57	-3.03	-0.51
	30-100	-1.54	-0.73	-1.03	-1.32	-2.04	-3.13	-1.97
	60-150	-1.82	-0.69	-0.96	--	--	--	-1.97

TABLE V

Rate of Accumulation of Heat in Calories per cm^2 per Second $x10^{-4}$ below the 30, 60, and 100 ft. Levels

Cruises	Depth	72°00'-10'	72°10'-20'	72°20'-30'	72°30'-40'	72°40'-50'	72°50'-73°00'	73°00'-10'
303-306	30	25.0	23.9	18.1	17.8	19.7	16.4	19.5
	60	24.5	17.2	12.8	--	--	12.8	15.0
	100	23.1	9.7	--	--	--	--	--
306-308	30	44.4	36.5	25.4	20.0	20.7	21.8	22.5
	60	54.0	25.8	18.6	--	--	13.2	15.4
	100	51.9	15.0	--	--	--	--	--
308-434	30	24.0	25.6	18.6	16.8	18.9	18.2	19.4
	60	26.8	18.7	13.5	--	11.6	12.7	15.4
	100	25.9	10.4	11.0	--	--	--	--
436-438	30	-24.0	-18.7	-18.3	-18.7	-23.0	-21.7	-23.0
	60	-25.7	-18.4	-13.3	- 9.3	-13.0	-14.7	-16.7
	100	-24.0	- 9.0	-11.0	--	--	--	--
438-440	30	-67.9	-47.4	-34.8	-27.4	-31.6	-31.2	-41.6
	60	-56.7	-34.5	-25.7	-13.6	-19.3	-22.1	-24.3
	100	-55.0	-20.0	-22.1	--	--	--	-15.5

TABLE VI

Coefficients of Vertical Eddy Conductivity in g. per cm. per sec.

Cruises	Depth	72°00'-10'	72°10'-20'	72°20'-30'	72°30'-40'	72°40'-50'	72°50'-73°00'	73°00'-10'
303-306	30	7.5	5.1	3.0	2.7	3.2	1.7	1.7
	60	?	20	34	--	--	2.7	3.4
	100	?	17	--	--	--	--	--
306-308	30	11	8.1	4.8	5.3	3.4	2.2	2.5
	60	?	20	17	--	--	2.2	2.2
	100	74	?	--	--	--	--	--
308-434	30	8.8	8.3	4.7	3.4	3.1	2.0	2.8
	60	?	18	14	--	1.7	1.6	2.0
	100	31	10	5.4	--	--	--	--
436-438	30	?	?	12	20	13	12	50
	60	33	?	9.4	12	7.7	6.5	12
	100	25	?	10	--	--	--	--
438-440	30	615	83	35	15	8.9	10	82
	60	37	47	25	10	9.5	7.1	12
	100	30	29	23	--	--	--	7.9

larger in the eastern end of the Sound, corresponding to the increasing tidal currents which probably are the major force in the generation of turbulence in these waters. There is also a depth relation that is expressed in two ways: First, the coefficient of conductivity decreases with increasing depth except where the stability is markedly greater at some particular level. Second, at any given depth there appears to be a decrease in conductivity when the mean depth of the underlying water is reduced, as in the central part of the Sound between 72°30' and 73°00'W. This probably is fundamentally a correction for the effect of bottom friction on current velocity. As previously described, the computed currents are means for the cross section, but the actual current at any depth and the resulting turbulence are reduced by proximity to the bottom.

The relationships that have been described may be stated as a simple proportionality

$$A_z \simeq \frac{Vf(Z)}{E}$$

in which A_z is the coefficient of vertical eddy conductivity, V is the mean current velocity of the cross section, $f(Z)$ is a function of the depth underlying the layer where the conductivity is to be determined, and E is stability. This is essentially similar to an equation for eddy viscosity developed by Fjeldstad (1).

The mathematical theory has not been developed further, but statistical procedures were used to develop an empirical equation based on the postulated proportionality. It is not necessarily applicable to other areas but is a good fit for the available Long Island Sound data. The equation is

$$A_z = \frac{VZ^2}{2E\times10^4}$$

in which V is measured in cm. per second, Z as mean depth in meters underlying the selected conductivity surface, and E is expressed as the change in σ_t per m. of depth. (For a more precise and standard definition see Sverdrup, Johnson and Fleming, reference 6, p. 416). Figure 32 shows the results in which the coefficients calculated from the temperature data for the 30 ft. (dots) and 60 ft. (crosses) levels are plotted against values determined from the equation, using the same subdivisions of 10' of longitude as previously but omitting the obviously incorrect negative values. There is considerable random variation, even though it was eliminated as far as possible by using averages for the spring warming period (cruises 303-434) and the autumn cooling period (436-440). The variation is believed to result from two main sources of error: (a) it is presumed that the original calculations contain some faulty generalizations about transport; (b) the quantity of salinity data is not sufficient to permit accurate estimates of stability. In spite of these unavoidable errors, the relationship expressed by the equation is highly significant statistically. From the oceanographic standpoint it is important to note that concordant results are obtained by two methods that are not only different in principle but also

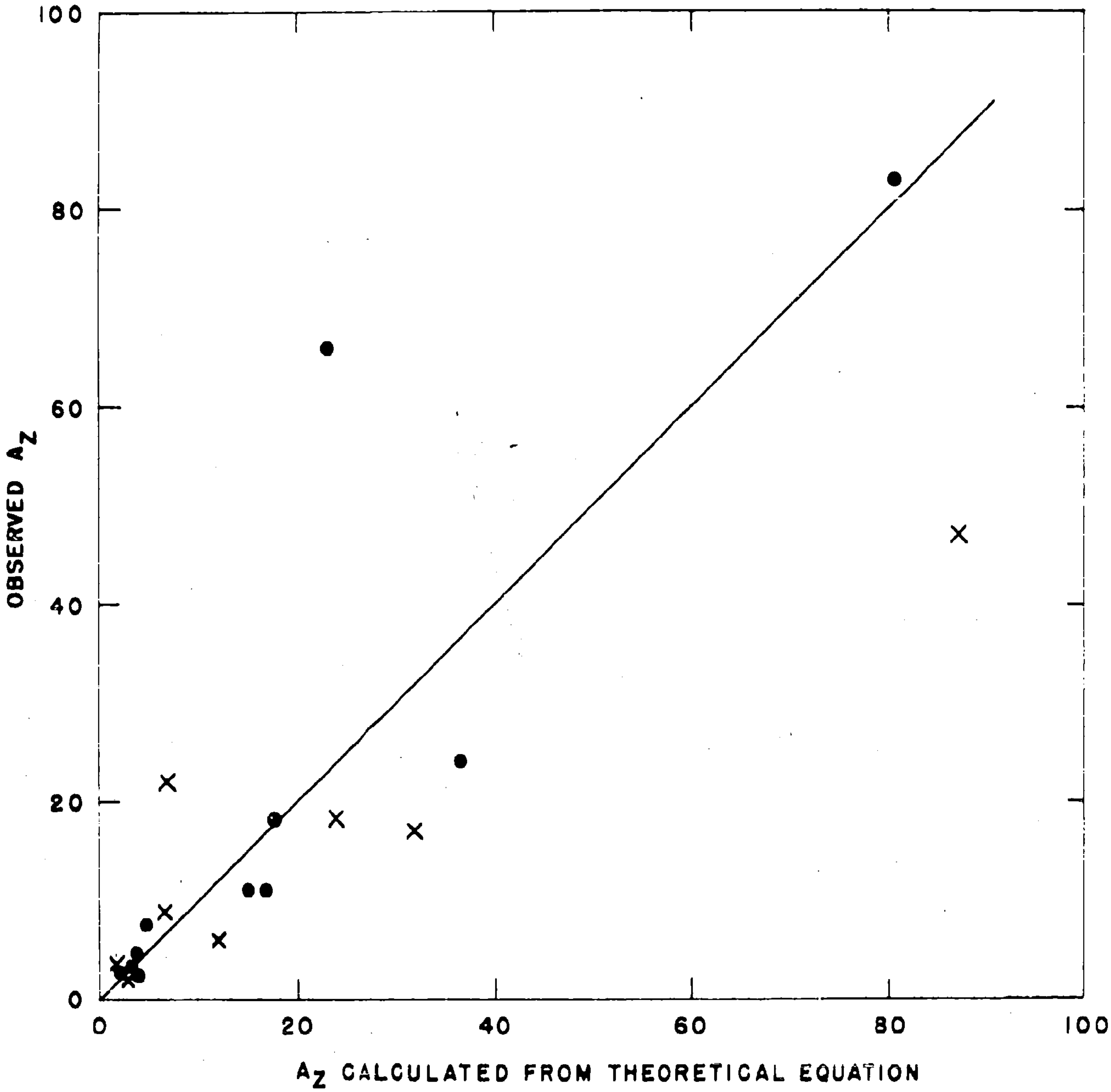


FIGURE 32. VERTICAL EDDY CONDUCTIVITY COEFFICIENTS.

with one exception are derived from different basic data. The exception is the vertical temperature gradient, which is utilized directly in the first equation and enters into the calculation of stability in the second one. Since the temperature gradient is much more important than salinity in determining the stability, a statistically valid relationship can be postulated between the rate of net passage of heat through a horizontal unit area (either up or down) and the current-depth expression in the second equation, that is,

$$\frac{\partial \gamma \varrho}{\partial t} \simeq VZ^2$$

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